
Summary Calorimeter Sessions at the Project X Summer Study

Project X Summer Study

David Hitlin (Caltech), Milind Diwan (BNL)



Assignment for DH/MD

- Convene a WG supporting the development of “the **"perfect"** high-energy photon detector: **next generation performance** in energy, position, direction and timing measurements in a high-rate environment.”
- Thus this is a view of the Project X (and pre-Project X) world through calorimeter-colored glasses



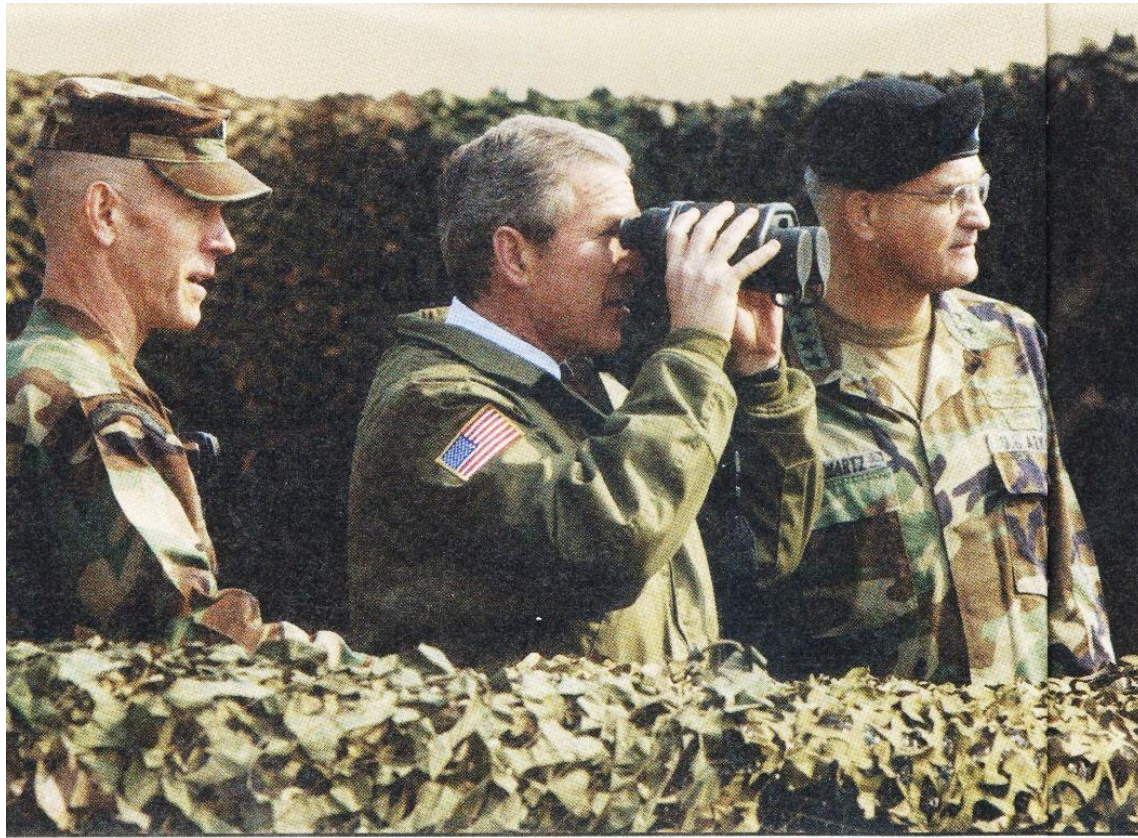
Assignment

- Thus this is a view of the Project X (and pre-Project X) world through calorimeter-colored glasses



Assignment

- Thus this is a view of the Project X (and pre-Project X) world through calorimeter-colored glasses



OMMANNEY/CONTACT PRESS IMAGES



Experiments with calorimeters (or not)

- Muons

- $\mu^- \rightarrow e^-$ conversion, $g-2$, $\mu^+ \rightarrow e^+e^+e^-$, $\mu^+ \rightarrow e^+\gamma$
- improving limits as well as improving the precision of branching fraction, conversion rate and $g-2$ measurements

- Kaons

- $K^+ \rightarrow \pi^+\nu\bar{\nu}$, $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$
- improving limits (K_L) and/or making branching fraction measurements (K^+) (K_L)

- $n\bar{n}$ oscillations

All these experiments pose different design and performance constraints on calorimeter requirements



- Efficiency, energy resolution, spatial resolution, angular resolution, time resolution, rate capability, radiation hardness, cost
 - Energy range is MeV to GeV (this is not the LHC or ILC)

I will discuss the physics objectives only in the sense of the derived requirements




Parallel sessions

Sat

 Date	Duration	Type	Title	Presenter
2012-Jun-16 11:00	00h10'		Introduction	Prof. HITLIN, David
2012-Jun-16 11:10	00h20'		MEG Calorimeter experience and upgrade	Prof. MOLZON, William
2012-Jun-16 11:30	00h25'		mu to e gamma (converted), eee	DEJONGH, Fritz
2012-Jun-16 11:55	00h25'		Mu2e calorimeter design and extrapolation	Prof. HITLIN, David
2012-Jun-16 16:00	00h25'		New crystal development	Dr. ZHU, Ren-yuan
2012-Jun-16 16:25	00h25'		PbF2/SiPM beam test	Dr. WINTER, Peter
2012-Jun-16 17:00	00h30'		Discussion	

Mon

2012-Jun-18 08:50	00h25'		Kaon experiment calorimetry requirements	Dr. LITTENBERG, Laurence
2012-Jun-18 09:15	00h25'		ORKA calorimeter - I	GATTO, Corrado
2012-Jun-18 09:40	00h25'		ORKA Calorimeter - II	Dr. MAZZACANE, Anna
2012-Jun-18 10:05	00h25'		KOPIO preradiator and calorimeter	Dr. POBLAGUEV, Andrei
2012-Jun-18 14:00	00h25'		Teflon-based scintillator	Dr. YEH, Minfang
2012-Jun-18 14:25	00h25'		KTeV Csl calorimeter	WORCESTER, Elizabeth
2012-Jun-18 14:50	00h10'		Calorimetry requirements for an nnbar experiment	Prof. KAMYSHKOV, Yuri
2012-Jun-18 15:00	00h30'		Discussion	

+Wed June 20 Organization for writing of FWP document(s)



Example Power Staging Plan for the Research Program

Program:	Onset of NOvA operations in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	~8 kW	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	8	8	8	8
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW



Muon experiments

- Bill Molzon reviewed the MEG experience & extrapolation
- Fritz Dejongh discussed a new idea for a next generation experiment that converts the photon
 - Measures three charged tracks
 - Baseline concept does not use a calorimeter
- DH discussed Mu2e
- Peter Winter discussed $g-2$



MEG status

- MEG is background limited above 10^{-12} branching fraction largely due to resolutions worse than proposal values
- Nonetheless, should reach a 90% CL sensitivity below 10^{-12} with data to be collected through ~ 1 year from now
- We are considering upgrades that could improve resolutions (and hence background rejection) and that could be implemented within ~ 2 years and yield significantly improved sensitivity within 5 years
 - Upgraded liquid xenon calorimeter – discussed here
 - New drift chamber – improved energy, angle measurements
 - New timing counters – improved intrinsic resolution, better match to drift chamber
 - Possible active target – improved angle determination
 - Muon stop rate increase by up to a factor of 3
- We plan to submit a proposal for the upgrades by the end of the year

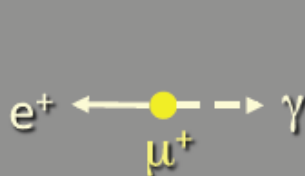
Bill Molzon



MEG signal and background signatures

Signal

$$\mu^+ \rightarrow e^+ \gamma$$



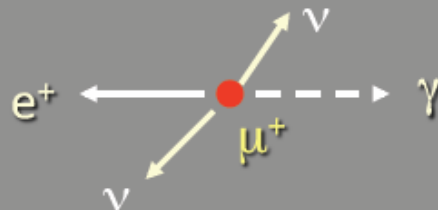
$$\theta_{e\gamma} = 180^\circ$$

$$E_e = E_\gamma = 52.8 \text{ MeV}$$

$$t_e = t_\gamma$$

Radiative decay background

$$\mu^+ \rightarrow e^+ \nu \nu \gamma$$



Suppressed by

- decay kinematics
- energy, angle resolution

Accidental background

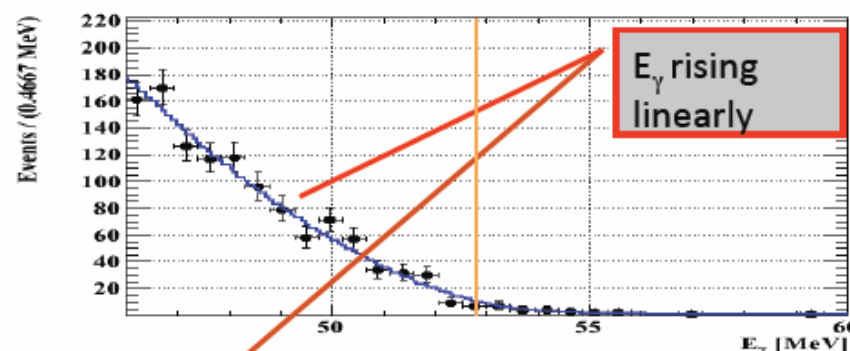
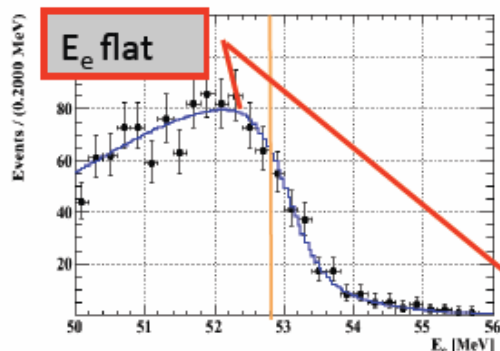
$$\mu^+ \rightarrow e^+ \nu \nu$$

$$+ \mu^+ \rightarrow e^+ \nu \nu \gamma \text{ or } e^+ e^- \rightarrow \gamma \gamma$$

Suppressed by

- Timing, energy, angle resolution

Dominates background at rates needed to reach 10^{-13}

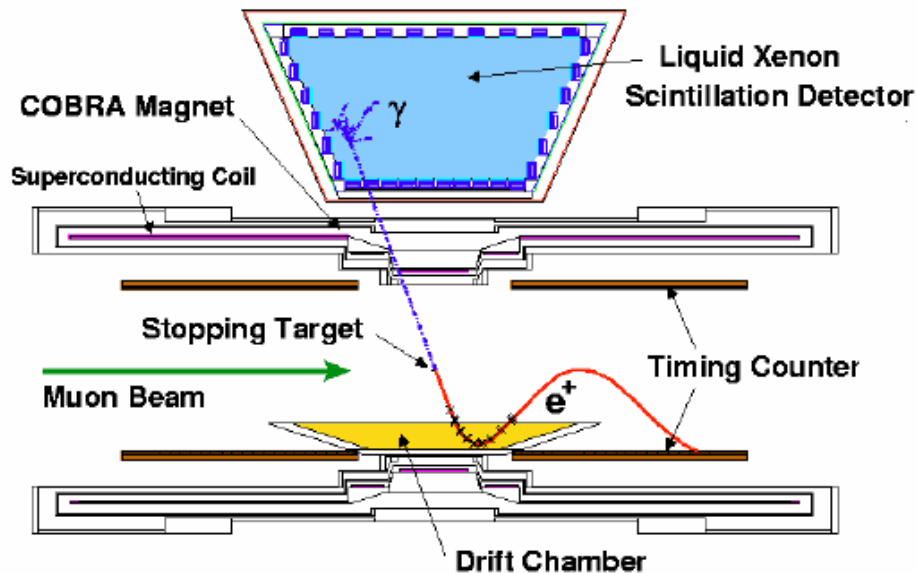


Bknd/signal proportional to $(\delta E_e)^1 \times (\delta E_\gamma)^2 \times (\delta \theta_{e\gamma})^2 \times (\delta t_{e\gamma}) \times \text{Rate}$

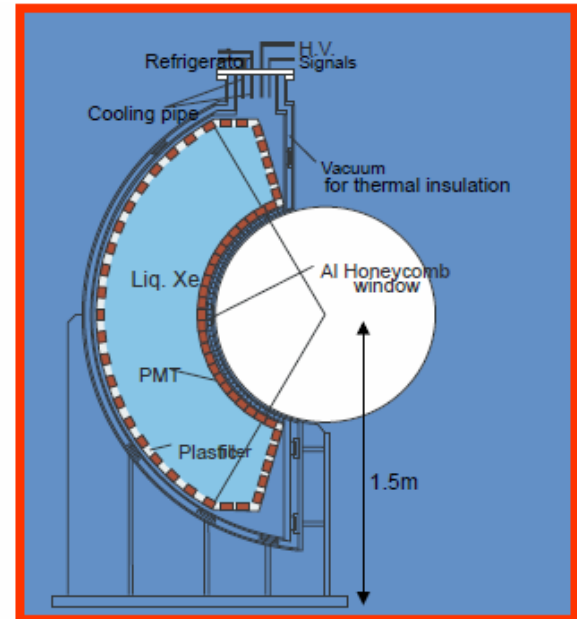
Bill Molzon



MEG Lxe calorimeter



- Relatively high light yield, uniform response
- No self-absorption of scintillation light: attenuation only from impurities
- ~1000 l liquid xenon (largest LXe volume)
- ~860 mesh phototubes on surface, in LXe
- Thin window to reduce photon conversions
- Goal is to measure photon properties:
 - Position: $\sigma_{\text{RMS}} = 5 \text{ mm}$
 - Time: $\sigma_{\text{RMS}} = 60 \text{ ps}$
 - Energy: $\sigma_{\text{RMS}} = \sim 900 \text{ keV at } 52 \text{ MeV}$

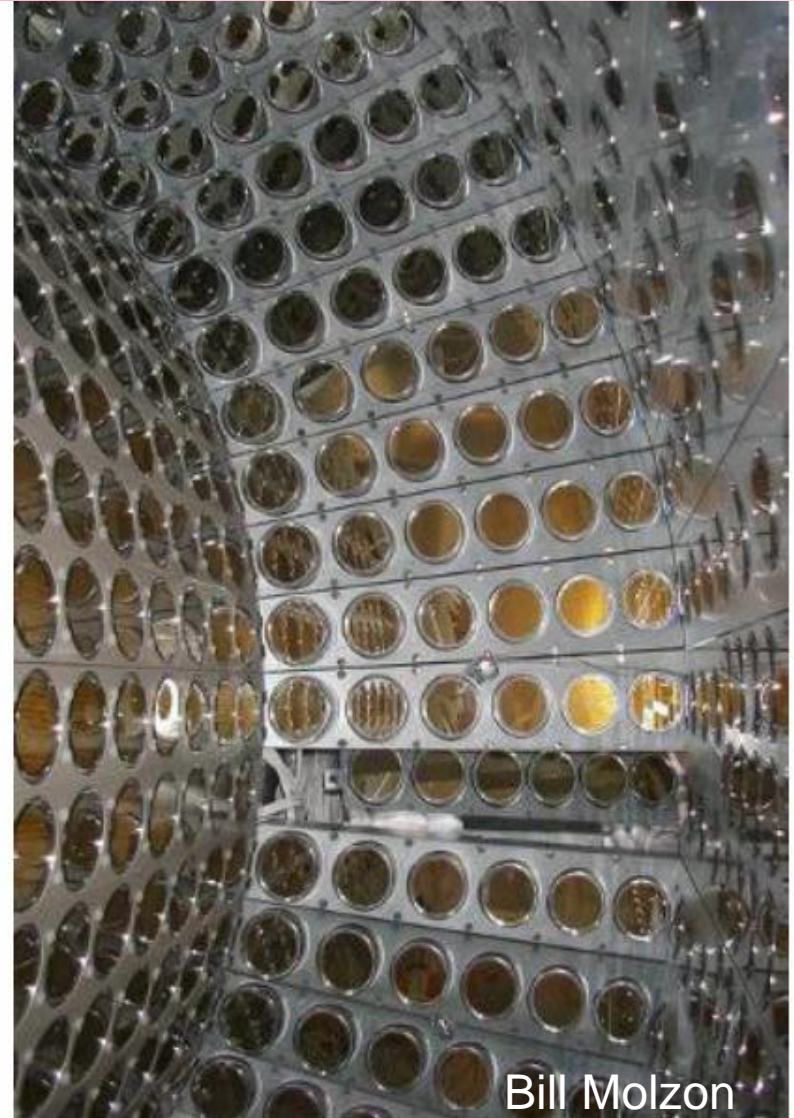


Density	2.95 g/cm ³
Boiling and melting points	165 K, 161 K
Energy per scintillation photon	24 eV
Radiation length	2.77 cm
Decay time	4.2, 22, 45 ns
Scintillation light wave length	175 nm
Scintillation light absorption length	> 100 cm
Attenuation length (Rayleigh scattering)	30 cm
Refractive index	1.74

Bill Molzon



MEG LXe calorimeter



Advantages and disadvantages of an LXe calorimeter

- Advantages

- Uniform ratio of light produced to energy deposited – fluctuations in fraction of ionization vs. light contributes to resolution at low energy if both are not measured
- No dead material in active volume
- High light yield – typically $\sim 200k$ photo-electrons for 53 MeV photon
- Signal is fast – decay time ~ 50 ns
- Very long absorption length limited by impurities
- Can fit for vertex position in all dimensions – important in determining photon time at vertex

- Disadvantages

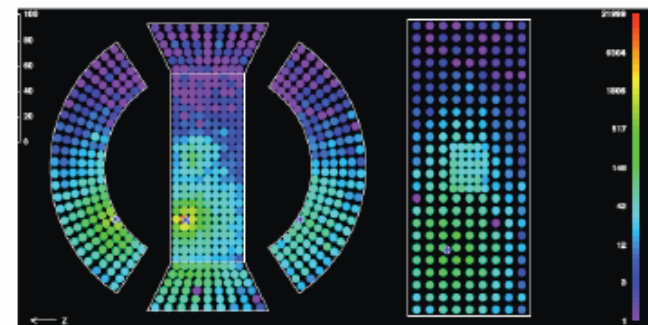
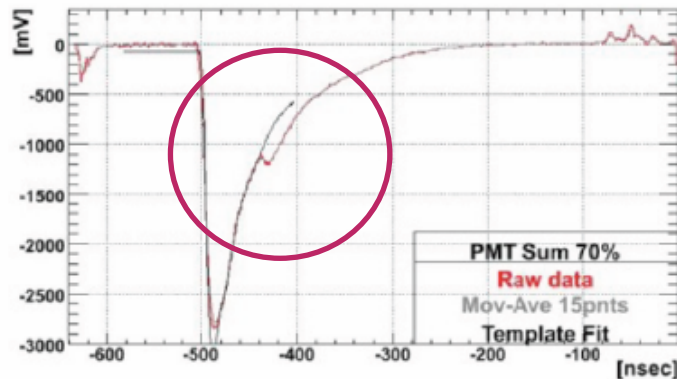
- Lack of optical separation means pileup is not easily isolated and affects signals far away
- Relatively short scattering length means light paths can be complicated, with reflections important to observed light distribution
- Need for cryostat reduces acceptance due to photon conversions in the cryostat wall
- Granularity of photocathode coverage on the walls complicates position and energy reconstruction for showers near the wall
- Calibrating each photo-detector for quantum efficiency times gain is arguably more difficult than it is for isolated detector elements

Bill Molzon

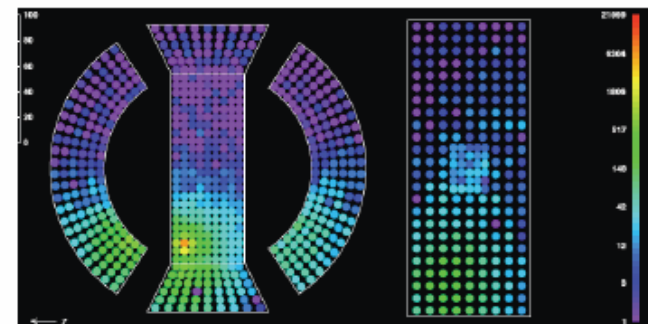


Pileup removal

- Events with clear pileup signal are identified and handled in a variety of ways
 - Events that have spatially separated showers corrected by removing secondary peak and replacing tube energies with templates based on light in unaffected regions
 - Events that have clear evidence of showers overlapping in time are fit to superposition of pulses of known shape.
 - Events that have evidence of pileup, but without clear separation in time or space are eliminated



before



Bill Molzon



Potential calorimeter upgrades

- Limitations to performance

- Resolution for early conversions worse due mostly to granularity of photo-cathode coverage
- Resolution near edges worse due to less than optimal pointing geometry of phototubes
- Stochastic variation of resolution and absolute calibration with 3D position in calorimeter that is not completely understood. Likely due at least in part to quantum efficiency and gain calibration errors.
- Effects of scattering, particularly with reflections off walls, complicates energy determination and likely contributes to resolution

- Upgrades being considered

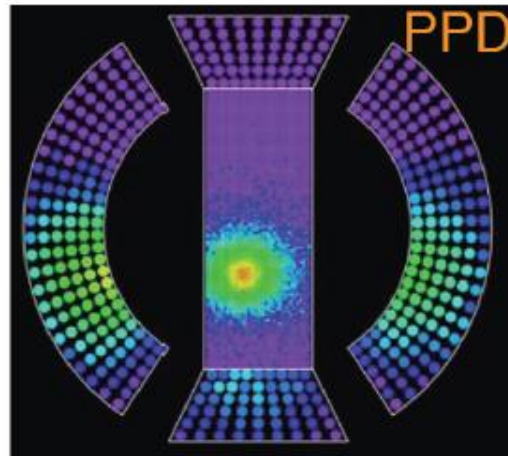
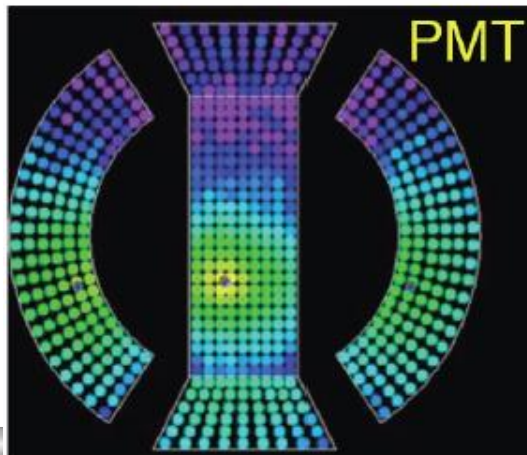
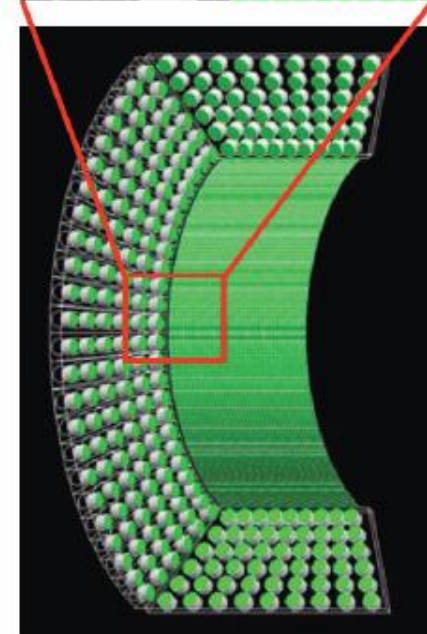
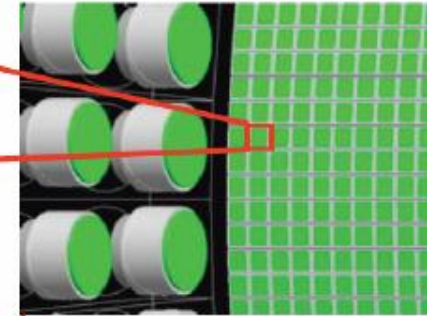
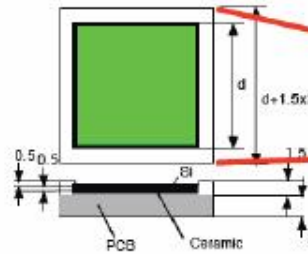
- Replace the phototubes on front face with MPPCs (SIPMs)
 - Reduce the granularity of the photo-cathode coverage
 - Possibly increase the photo-cathode coverage
 - Less dead space and material at the front face – increased efficiency
- Use non-reflective coating on the interior face of the cryostat to reduce reflections
 - Plenty of photo-electrons, so decrease in total light yield is not a problem
 - Will likely improve all of energy, timing, position resolution
- Modify phototube orientation on side walls to be in a single plane
 - Reduces shadowing
- Increase active size in the Z direction
 - Improves light collection and resolution

Bill Molzon



MPPCs for the front face of the calorimeter

- Use large area MPPCs 12x12 mm²
- A few potential suppliers
- Mount them on ceramic base + printed circuit board
- Up to 3500 devices
- Many things need to be studied
 - Intrinsic non-linearity with large dynamic range – correctible
 - Absorption of vuv photons in protective layer – remove it
 - Reflection from silicon surface – anti-reflective coating
 - Cross-talk between pixels – cut channels
 - After-pulsing, worse at low temperature
 - Potential for increased noise summing many signals



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 - Muon stop rate increase by up to a factor of 3
- We plan to submit a proposal for the upgrades by the end of the year

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$\mu^+ \rightarrow e^+ \gamma$ with converted γ

- Goal: Path to 10^{-16} sensitivity using
 - Intense stopped muons beams from Project-X
 - Monolithic pixel detectors
 - Time of flight
 - Calorimetry?
- Existing branching fraction limits

MEGA: $< 1.2 \times 10^{-11}$ (1999)

Using converted photons

converter: 9% radiation length (in each of 3 layers)

6% duty cycle

1.5×10^7 stopped muons/sec

MEG: $< 2.4 \times 10^{-12}$ (2010)

Using LXe calorimeter

Expects to reach $\text{few} \times 10^{-13}$



Sensitivity goals with Project X cold μ beam

- Use project X to increase R_μ (the rate of stopped muons) and signal rate
- **Problem:** Accidental coincidence rate increases as R_μ^2 (instantaneous)
- Need
 - 100% duty cycle
 - Thin converter
 - Thin detectors
 - Resolution limited only by energy loss and multiple scattering
- Will need 3×10^{11} stopped muons/sec
 - Mu2e: 5×10^{10} with 8 KW proton power
- However, need it with small, thin target
 - A challenge for Project X, but seems plausible

What if we discover $BR = 10^{-14}$?

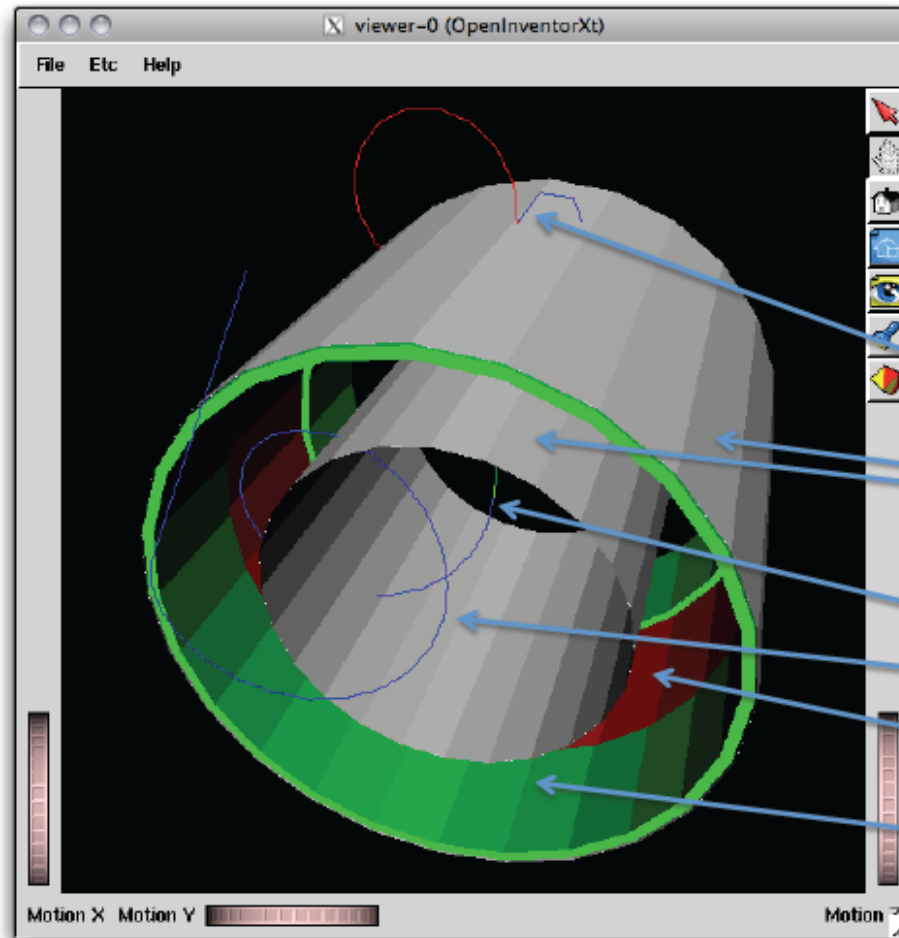
Can increase R_μ by 100 and have $S/N = 1$

Would obtain 10^4 events and precision BR!

- Need 3×10^{13} stopped muons/sec
 - Advanced muon cooling at a high project X stage #



A simple geometry seems plausible



Target radius ~ 2 cm

$B = 0.5$ T

Positron $R = 35$ cm

Converted photon

Double pixel layers
 $R = 47$ cm and 75 cm

$\mu \rightarrow e \gamma$ decay from stopped muon

Positron

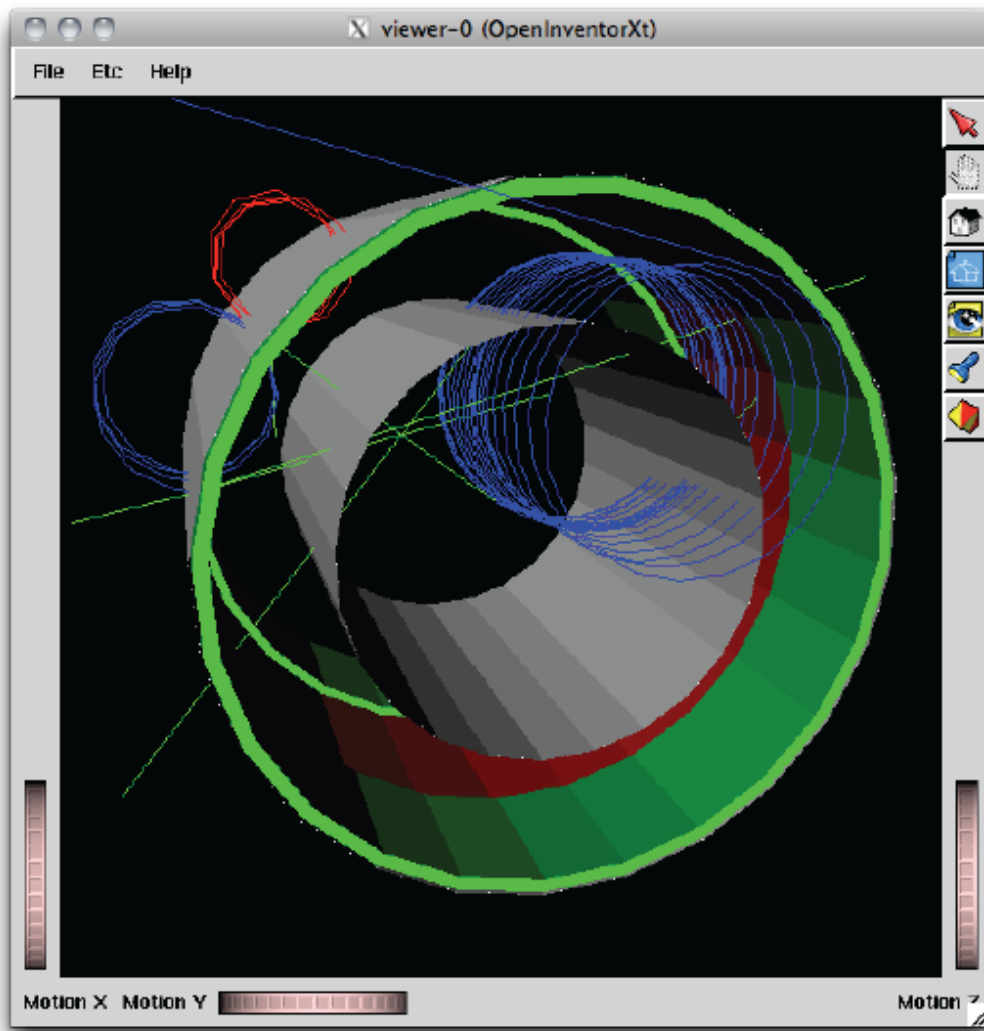
Converter

Calorimeters or tof
triggering, tof

Needs square meters of pixels



Issues



- Need target extended in z (~ 150 cm), since γ is pointing to potential vertex from a long distance
- TOF?
- Calorimetric confirmation?



Production Solenoid

- Production target
- Graded field

- Delivers ~ 0.0016 stopped μ^- per incident proton
- 10^{10} Hz of stopped muons

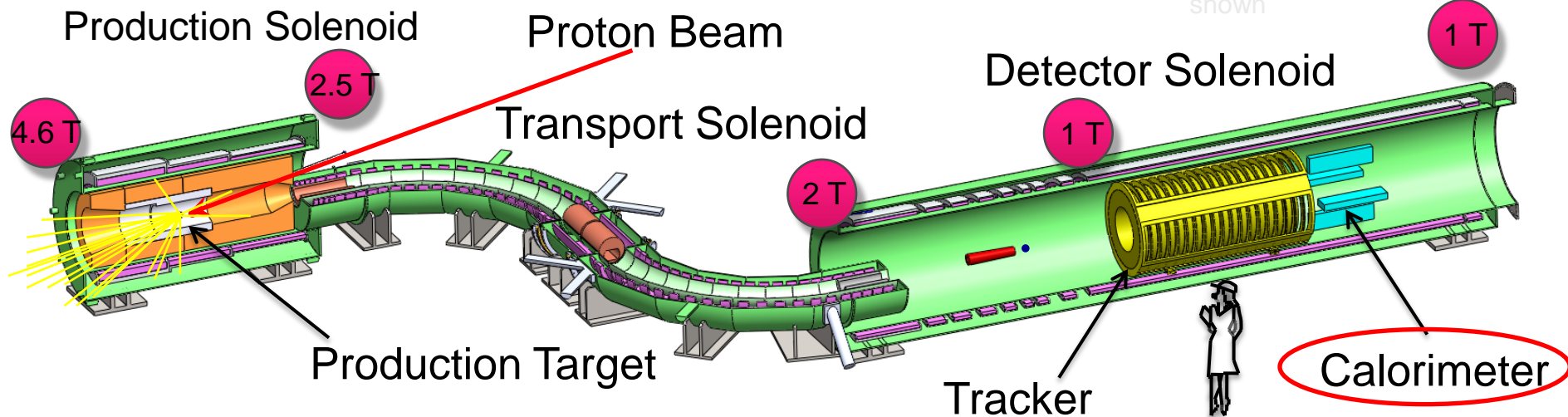
Transport Solenoid

- Collimation system selects muon charge and momentum range
- Pbar window in middle of central collimator

Detector Solenoid

- Muon stopping target
- Tracker
- Calorimeter
- Warm bore evacuated to 10^{-4} Torr

Cosmic Ray Veto not shown



Calorimeter requirements

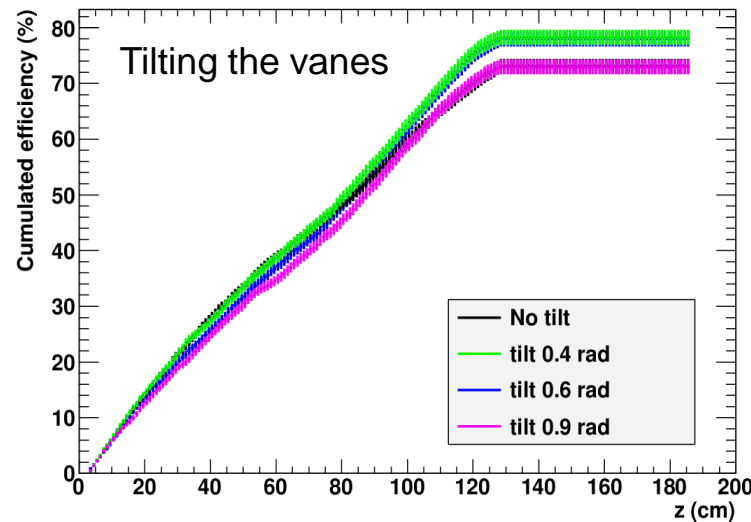
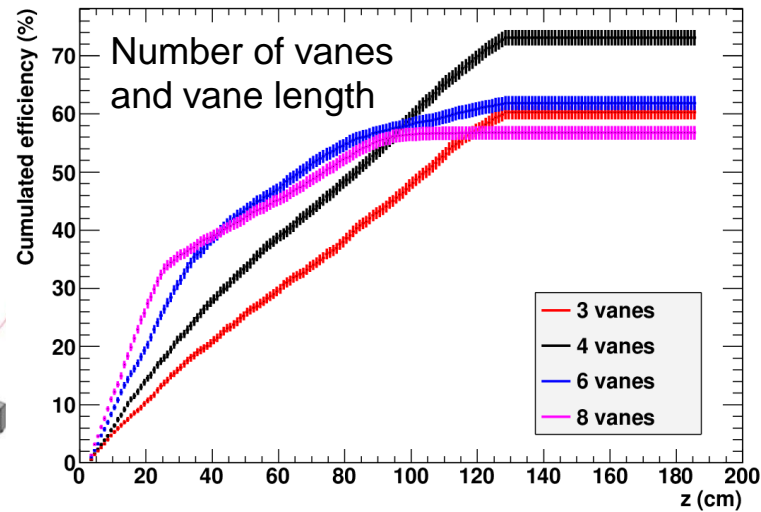
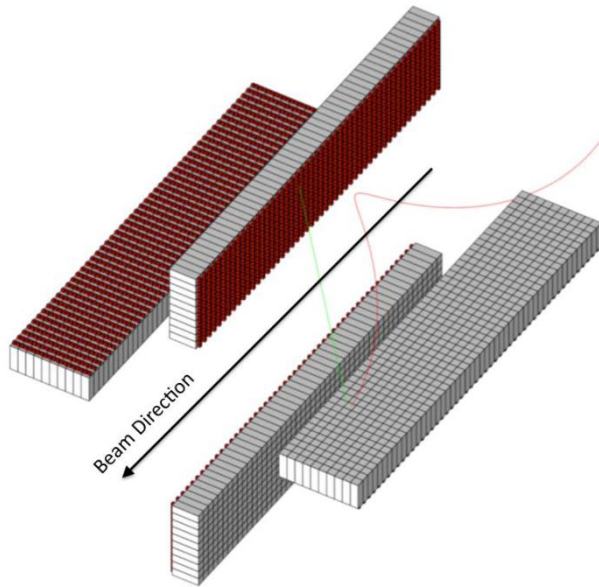
The purpose of the calorimeter is to confirm that a reconstructed track of a $\mu \rightarrow e$ conversion electron candidate is well-measured, and was not created by a spurious combination of hits in the tracker.

1. Measure the position of the conversion electron $\rightarrow \sigma(x) \leq \mathcal{O}(1 \text{ cm})$.
2. Compare the energy deposited in the calorimeter to the reconstructed track momentum $\rightarrow \sigma(E) \leq \mathcal{O}(2\%)$, with an uncertainty in the energy scale small compared to the resolution.
3. Compare the time of the energy deposit in the calorimeter to the time determined from the tracker $\rightarrow \sigma(t) \leq \mathcal{O}(1 \text{ ns})$.
4. Provide particle identification to separate, for example, electrons from muons.
5. Provide a trigger that can be used for event selection
6. Maintain functionality in a 50 Gy/year radiation environment with light yield loss $< 10\%$

Requirements met by an array of ~ 2100 LYSO crystals ($11 X_0$)



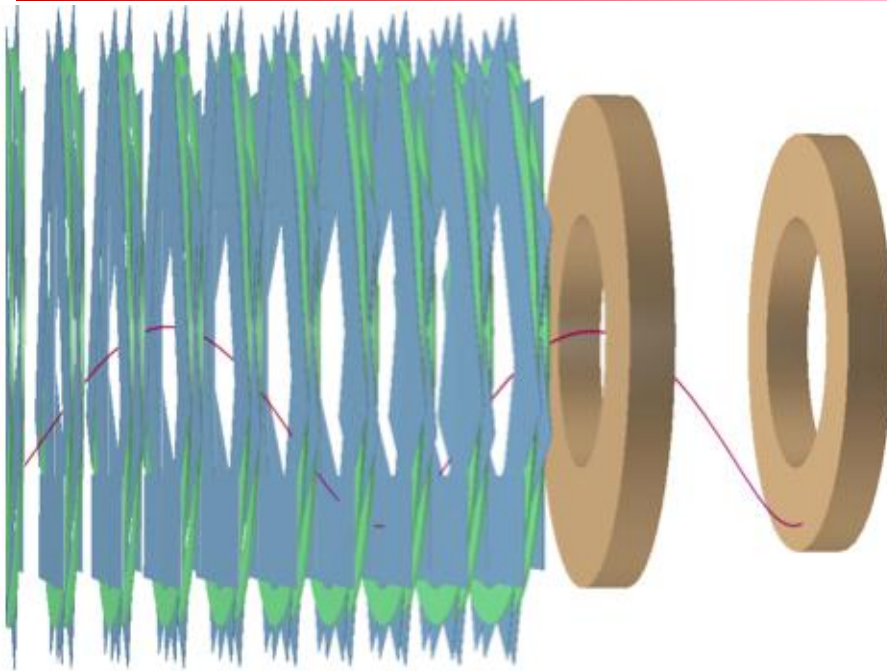
Calorimeter - vane design



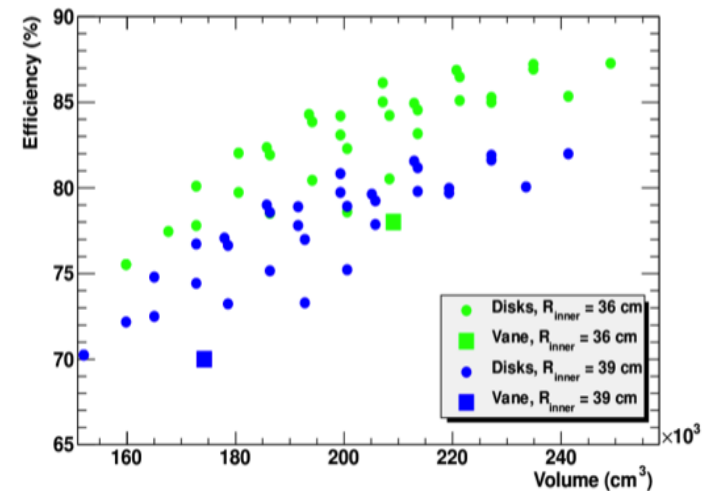
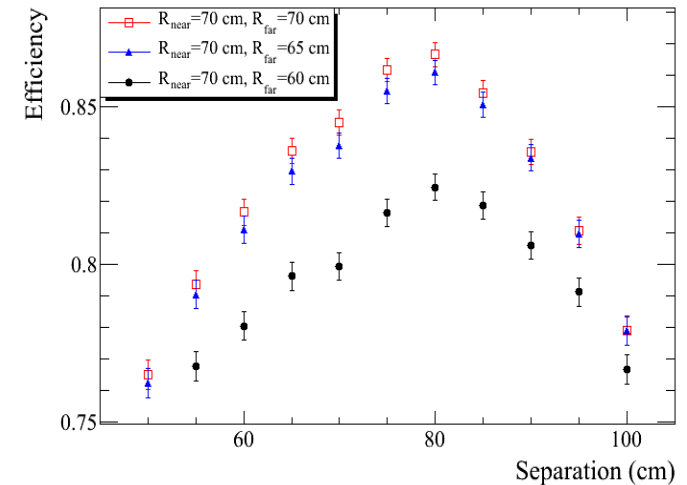
B. Echenard



Calorimeter - Disk Geometry



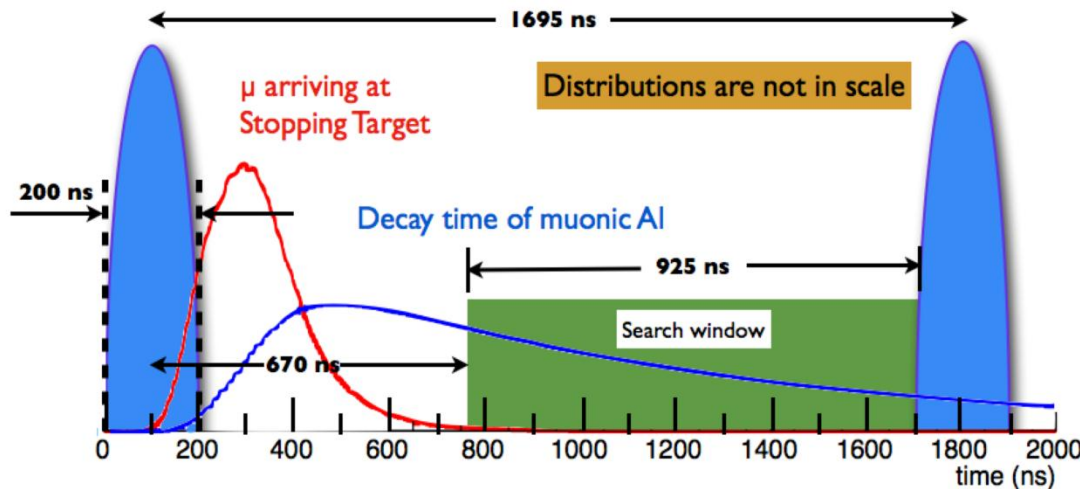
- ❑ Alternate geometry: two discs separated by $\frac{1}{2}$ wavelength of the helical trajectory of the conversion electron
- ❑ Provides greater efficiency for a given crystal volume and substantially higher efficiency (84% of good tracks in the fiducial volume) than the vane geometry
- ❑ The disks face the target \Rightarrow photon and neutron background from muon capture is seen head on.



Works for $\mu^+ \rightarrow e^+e^+e^-$



Time structure of the Mu2e beam



Muon nuclear capture and Decay in Orbit (DIO)

Muon capture on Al has two dominant final states:

- nuclear capture, $\sim 60\% \Rightarrow n, p, \gamma$
- muon DIO, $\sim 40\% \Rightarrow$ high energy tail is an irreducible background to μ to e conversion. Suppressed by excellent momentum resolution

Required extinction $< 10^{-10}$

Prompt beam-related background

Suppressed by a delayed “live” window which starts about 670 ns after the beam pulse.

Radiative Pion Capture

Negative pions stopped in the Al target:



About 2×10^{-4} decay electrons are in the momentum signal region for 3.6×10^{20} pot

Project X CW linac allows further optimization of this time structure (shorter pulse, for example) – Steve Holmes presentation



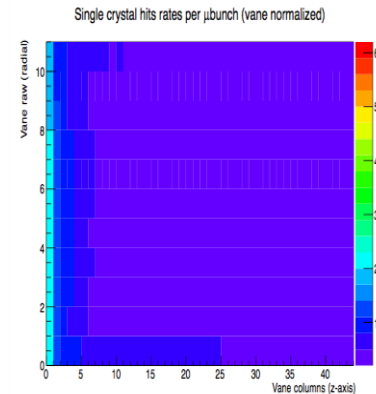
Calorimeter hit rates (vanes)

- Crystal hits in a microbunch

	Total crystal hits (Rate in MHz)	Hits from generated n	Hits from tracks born outside the vanes (sec neutrons + γ)	Hits from tracks born in other vanes (electrons + γ)	Hits from showers only (electrons + γ + HI)	Hottest crystal rate (MHz)
B050	768 (454)	0.5	245	9	512	2.2 (Raw 5 Col 1)

- Crystal hits in live window ($t > 700\text{ns}$)

	Total crystal hits (Rate in MHz)	Hits from generated n	Hits from tracks born outside the vanes (sec neutrons + γ)	Hits from tracks born in other vanes (electrons + γ)	Hits from showers only (electrons + γ + HI)
B050	500 (503)	0	147	6	348



Can the Mu2e calorimeter function at Project X?

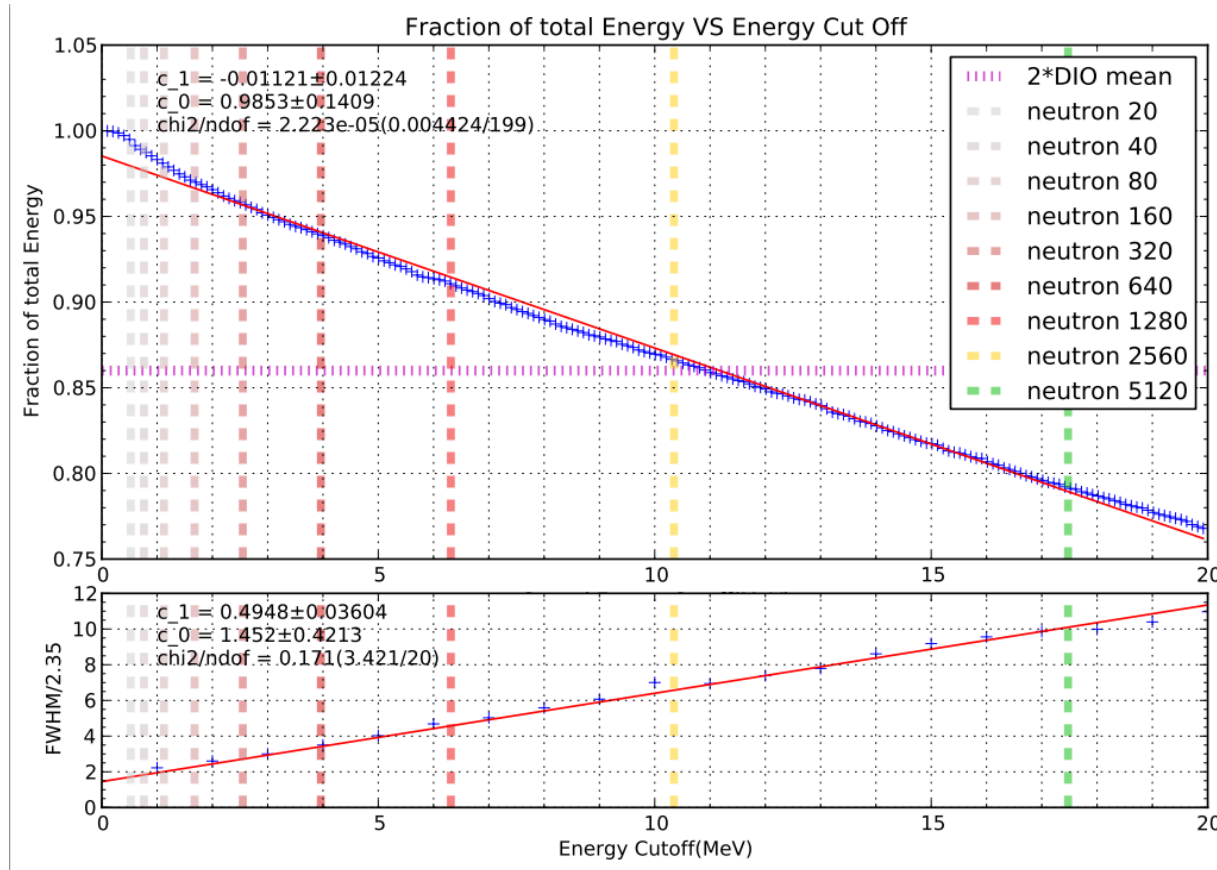
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1. Measure the position of the conversion electron $\rightarrow \sigma(x) \leq \mathcal{O}(1 \text{ cm})$. *crystal size*
 r_M
2. Compare the energy deposited in the calorimeter to the reconstructed track momentum $\rightarrow \sigma(E) \leq \mathcal{O}(2\%)$, with an uncertainty in the energy scale small compared to the resolution. $\tau_{\text{scint}}, t_{\text{int}}$
3. Compare the time of the energy deposit in the calorimeter to the time determined from the tracker $\rightarrow \sigma(t) \mathcal{O}(\leq 1 \text{ ns})$. t_r
4. Provide particle identification to separate, for example, electrons from muons. t_r
5. Provide a trigger that can be used for event selection t_r
6. Maintain functionality in a ~~50~~ 500 Gy/year radiation environment with light yield loss < 10% 500-5000
rad hardness



Effect of background on conversion electron resolution

- “Salt and pepper” background included in energy clusters
 - Deteriorates energy resolution



At PX Stage 1,
requirements can
likely be ~met by
shortening
integration time.

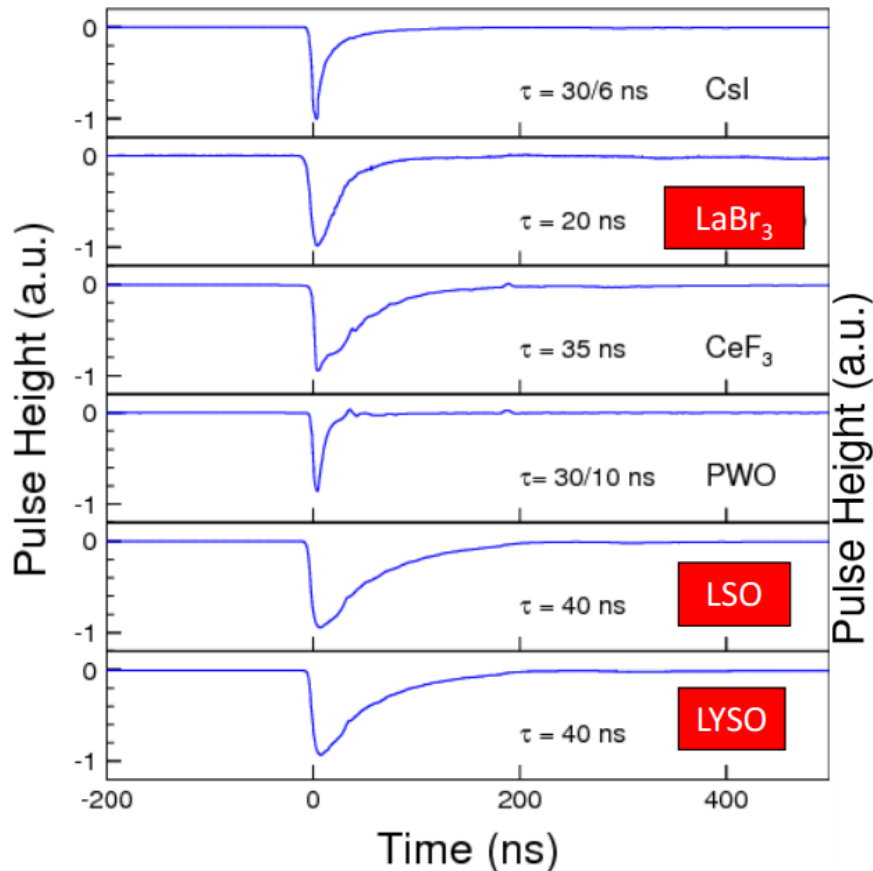
Tracker ??????

At later stages,
either a new
technique or a
faster crystal will
be needed

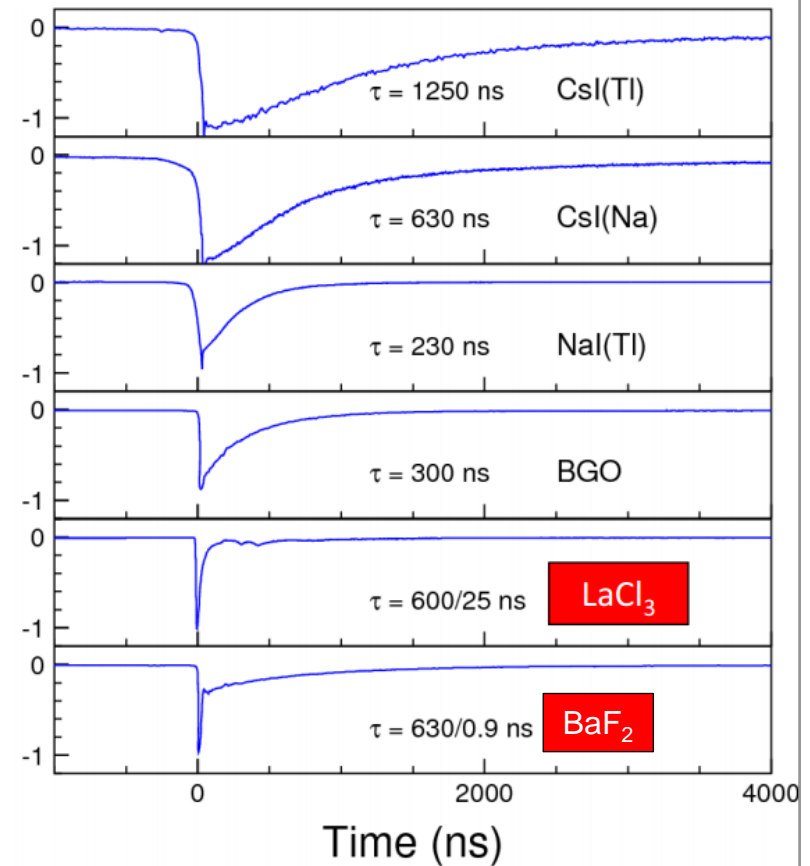


Scintillation pulse shapes

Fast Scintillators

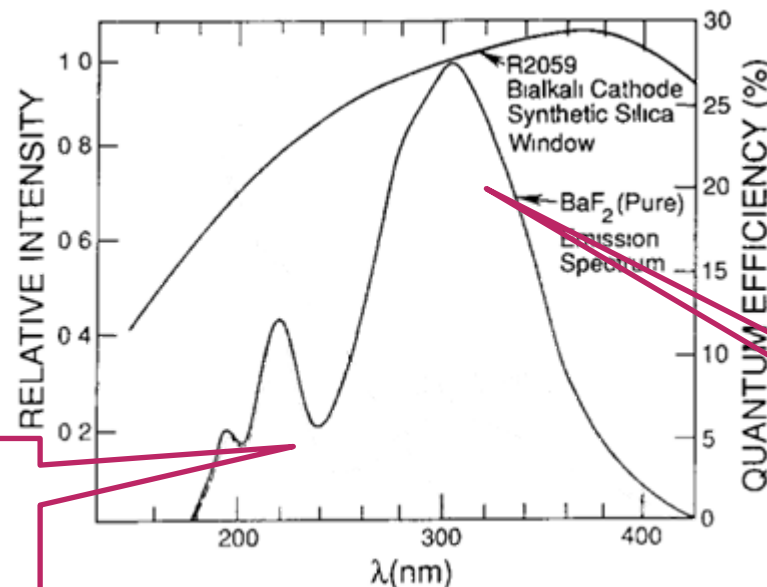


Slow Scintillators



"If a tree falls ...

- "If a tree falls in a forest and no one is around to hear it, does it make a sound?"
- "If a crystal emits light and no one is around to see it, does it scintillate?"
- BaF_2 is among the fastest scintillating crystals (0.6-0.8ns), but it has a larger, slower, component (630ns)



Total light output
 1.2×10^4 photons/MeV

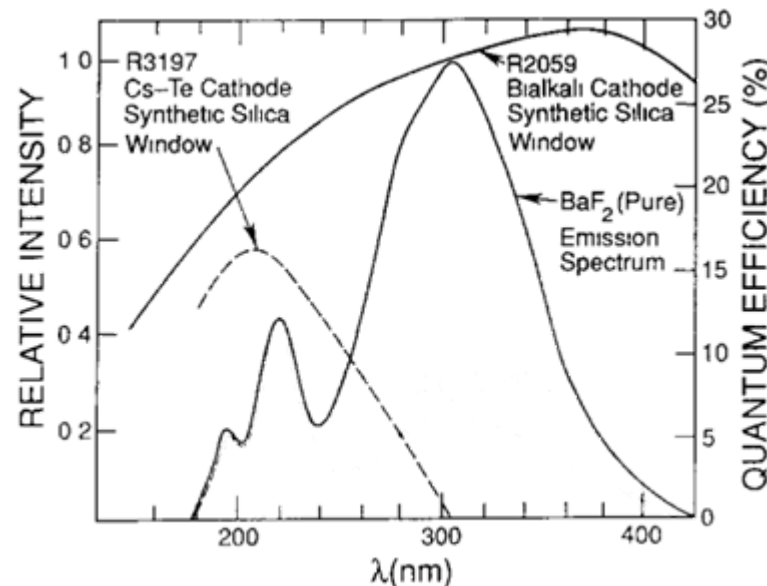
15%
600-800 ps

85%
630 ns



"If a tree falls ...

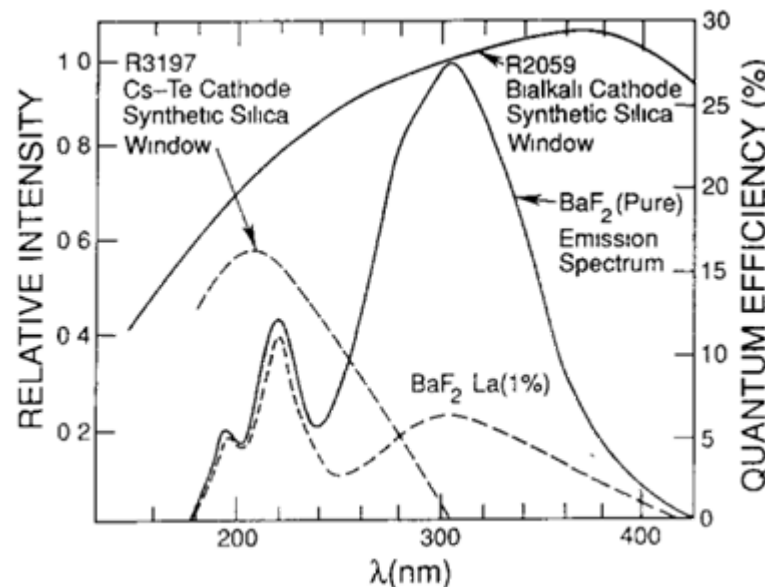
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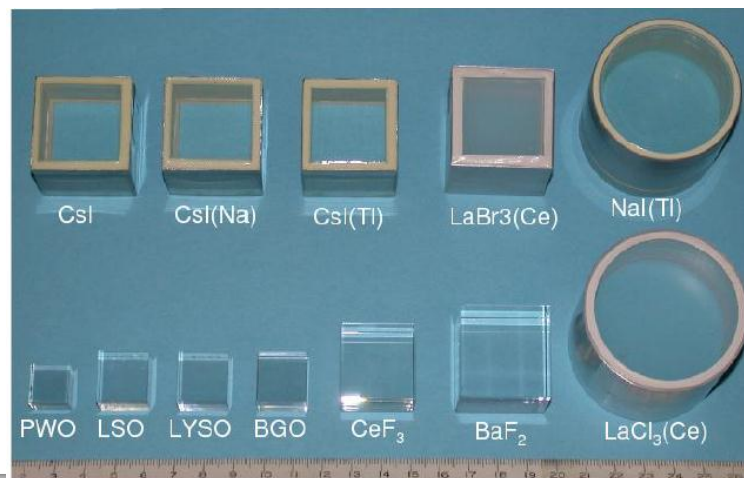
Can solar blind SiC APDs, which now exist at 100 μm diameter, be made larger, and combined with a thin film optical filter, to make BaF_2 a truly fast scintillator?



A fast crystal “figure of merit”

Crystal Scintillators	Relative LY (%)	A ₁ (%)	τ_1 (ns)	A ₂ (%)	τ_2 (ns)	Total LO (p.e./MeV, XP2254B)	LO in 1ns (p.e./MeV, XP2254B)	LO in 0.1ns (p.e./MeV, XP2254B)	LY in 0.1ns (photons/MeV)
BaF ₂	40.1	91	650	9	0.9	1149	71.0	11.0	136.6
LSO:Ca,Ce	94	100	30			2400	78.7	8.0	110.9
LSO/LYSO:Ce	85	100	40			2180	53.8	5.4	75.3
CeF ₃	7.3	100	30			208	6.8	0.7	8.6
BGO	21	100	300			350	1.2	0.1	2.5
PWO	0.377	80	30	20	10	9.2	0.42	0.04	0.4
LaBr ₃ :Ce	130	100	20			3810	185.8	19.0	229.9
LaCl ₃ :Ce	55	24	570	76	24	1570	49.36	5.03	62.5
NaI:Tl	100	100	245			2604	10.6	1.1	14.5
CsI	4.7	77	30	23	6	131	7.9	0.8	10.6
CsI:Tl	165	100	1220			2093	1.7	0.2	4.8
CsI:Na	88	100	690			2274	3.3	0.3	4.5

Motivates R&D on fast crystals and appropriate solid state readout



Ren-yuan Zhu



Fast scintillating crystals

	LSO/LYSO	YSO	GSO	BaF ₂	CsI	CeF ₃	CeBr ₃	LaBr ₃	LaCl ₃
Density (g/cm ³)	7.40	4.54	6.71	4.89	4.51	6.16	5.10	5.29	3.86
Radiation Length (cm)	1.14	3.04	1.38	2.03	1.86	1.70	1.96	1.88	2.81
Molière Radius (cm)	2.07	2.87	2.23	3.10	3.57	2.41	2.97	2.85	3.71
Interaction Length (cm)	20.9	27.3	22.2	30.7	39.3	23.2	31.5	30.4	37.6
Z value	64.8	33.3	57.9	51.6	54.0	50.8	45.6	45.6	47.3
dE/dX (MeV/cm)	9.55	6.70	8.88	6.52	5.56	8.42	6.65	6.90	5.27
Emission Peak ^a (nm)	420	420	430	300 220	420 310	340 300	371	356	335
Refractive Index ^b	1.82	1.80	1.85	1.50	1.95	1.62	2.3	1.9	1.9
Relative Light Yield ^{a,c}	100	40		42 4.8	4.2 1.3	8.6	144	153	15 49
Decay Time ^a (ns)	40	70	65	650 0.9	30 6	30	17	20	570 24
d(LY)/dT ^d (%/°C)	-0.2	-0.3	-0.7	-1.9 0.1	-1.4	~0	-0.1	0.2	0.1

Ren-yuan Zhu



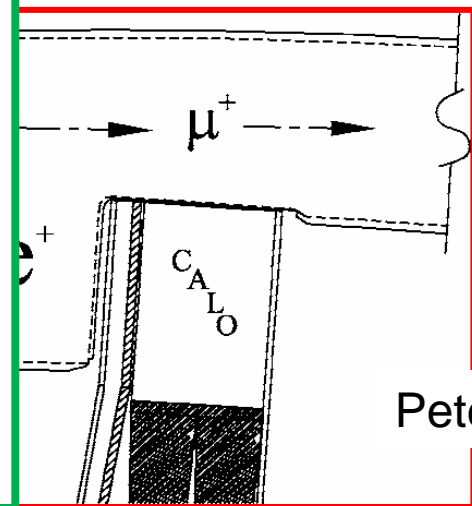
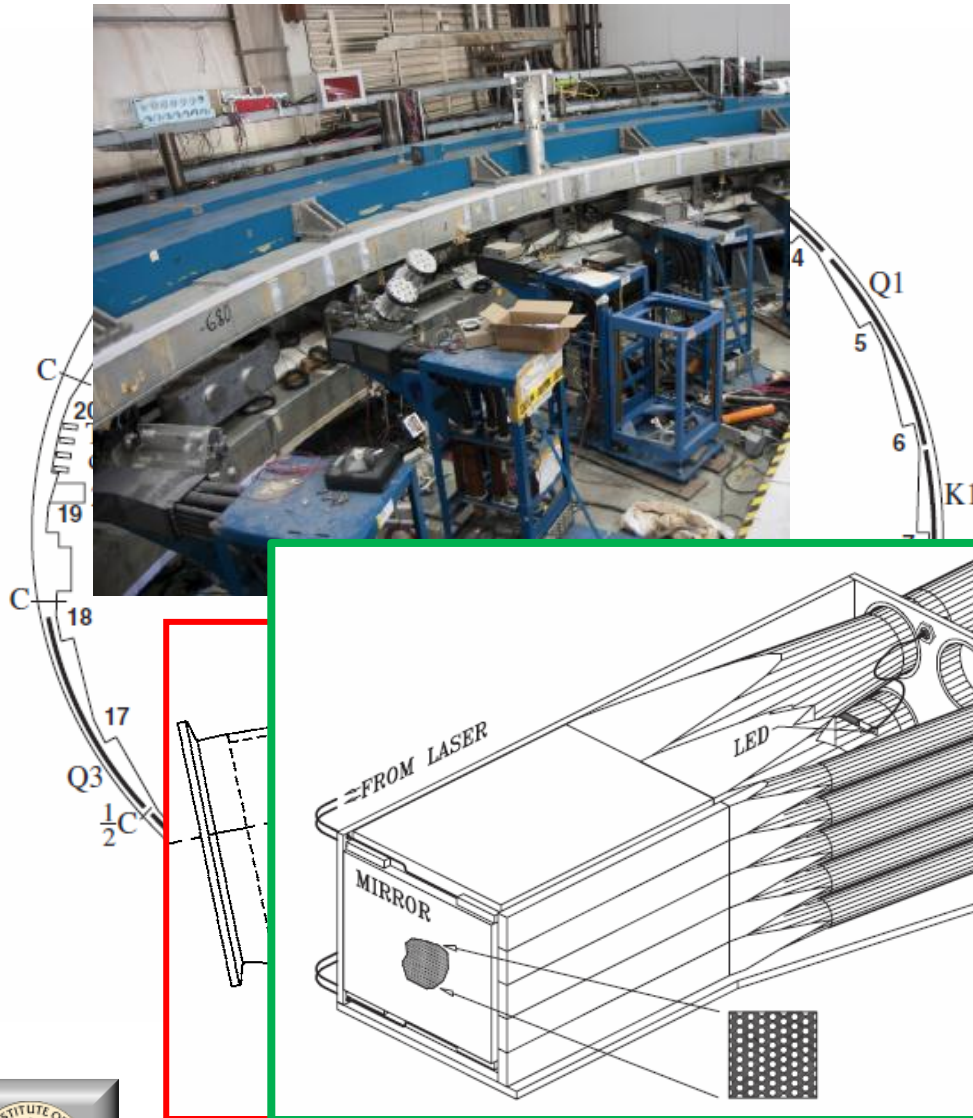
g-2 has calorimeters to detect the decay electron

24 calorimeter stations

Scallop vacuum chamber

Lead scintillating fiber
calorimeter with PMTs

Full waveform digitized

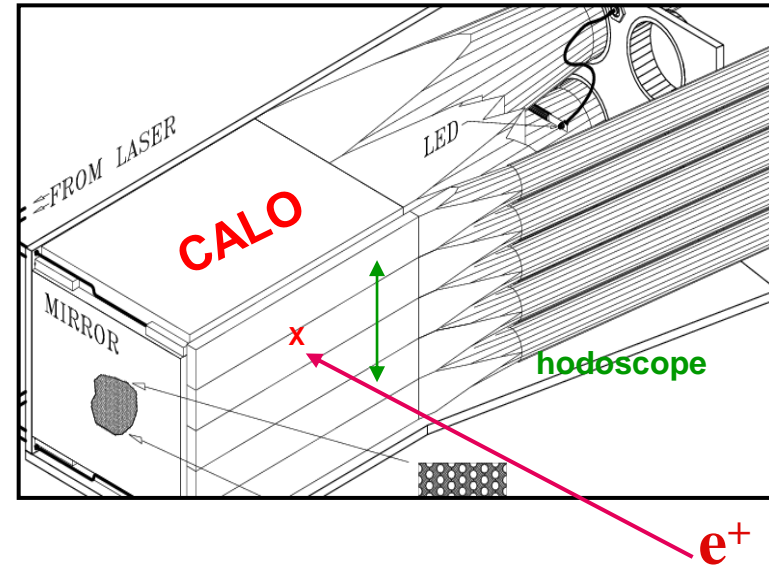


Peter Winter



Design constraints

- **Detector response: fast scint**
 - ◆ **Pulse-to-pulse separation ~ 5 nsec**
- **Gated off for ~10 μ s was required**
 - ◆ **Back on in 1 μ s to 99.9% of gain**
 - ◆ **Stability of gain a challenge (need <0.1%, full simulation required)**
- **Pileup algorithms clever,**
 - ◆ **But, 0.08 ppm systematic remained from percent-level pileup (see later)**





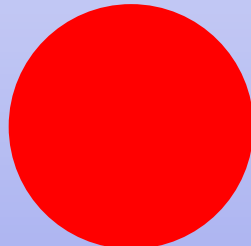



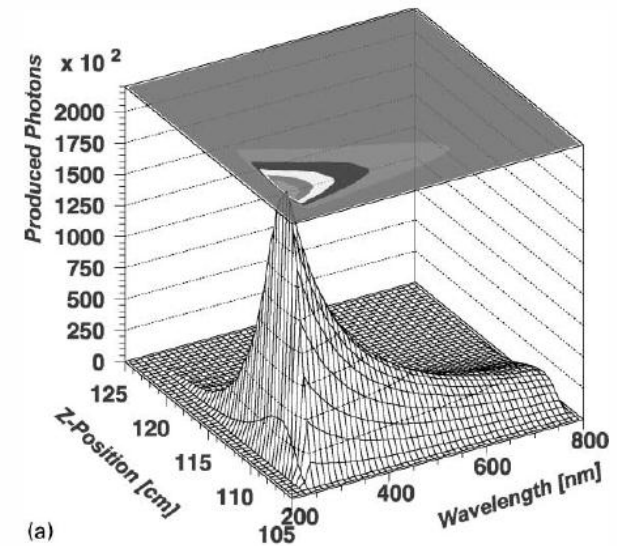
- **E821 Instantaneous rates:**
 - At ~25 μ s after injection, $E > 1$ GeV: Each calo sees up to 0.9 MHz
 - With “no” threshold, the rate is up to 1.8 MHz
- **New Experiment Challenge:**
 - Determine average rate; it could be higher (up to 3x !)
 - How to manage pileup and keep average rate on photo-detector “low”?

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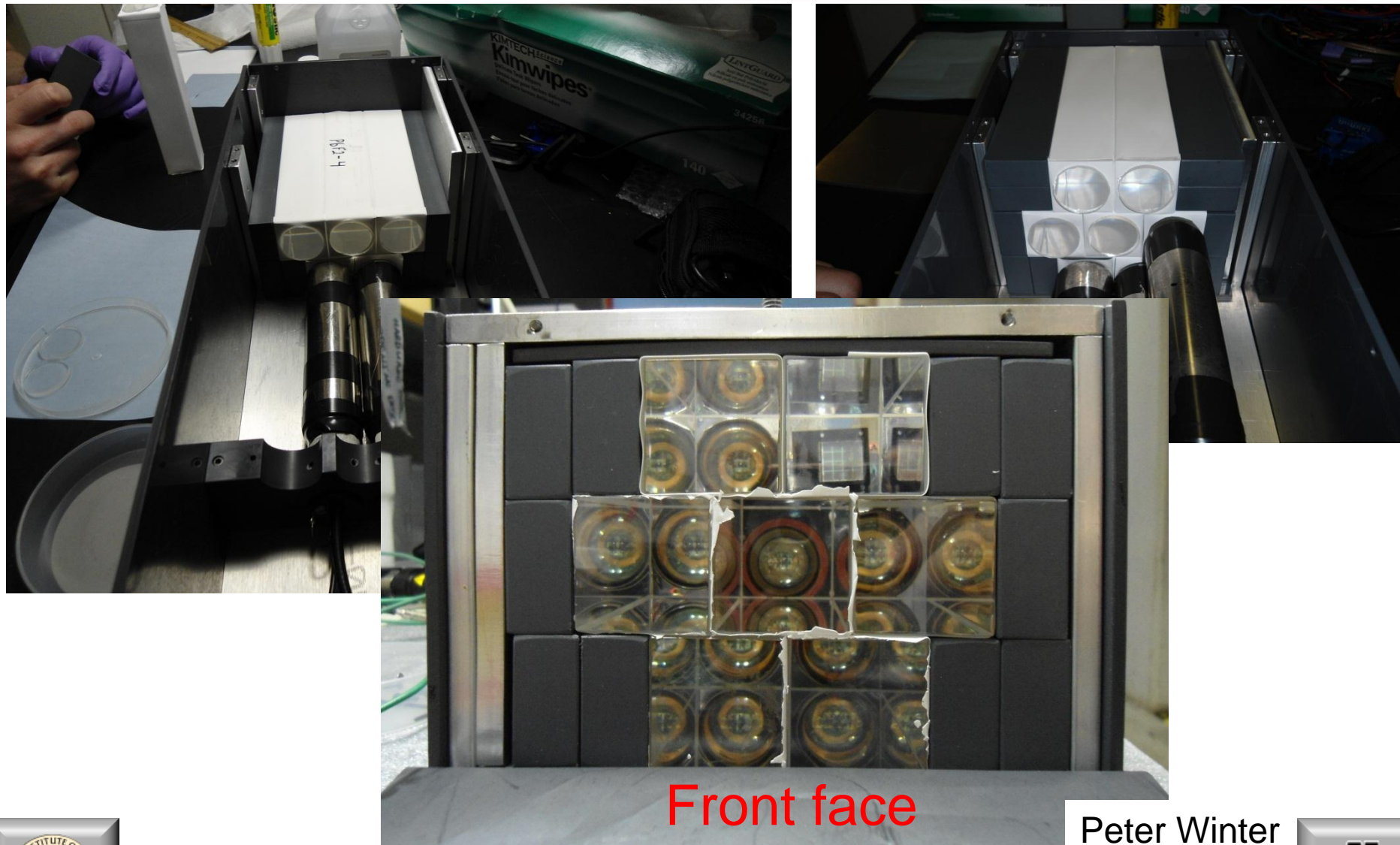
Candidate radiators

Material	PbF ₂	PbWO ₄ (undoped)	W / SciFi
Type	Cerenkov	Cerenkov + Scintillation	Sampling
Radiation length	0.93 cm 	0.89 cm 	0.69 cm 
Moliere radius	1.8 cm (Cerenkov) 	2.0 cm 	1.73 cm 
Typical resolution	3 – 5 %	2 – 5 %	12 %



PbF₂ Cerenkov spectrum

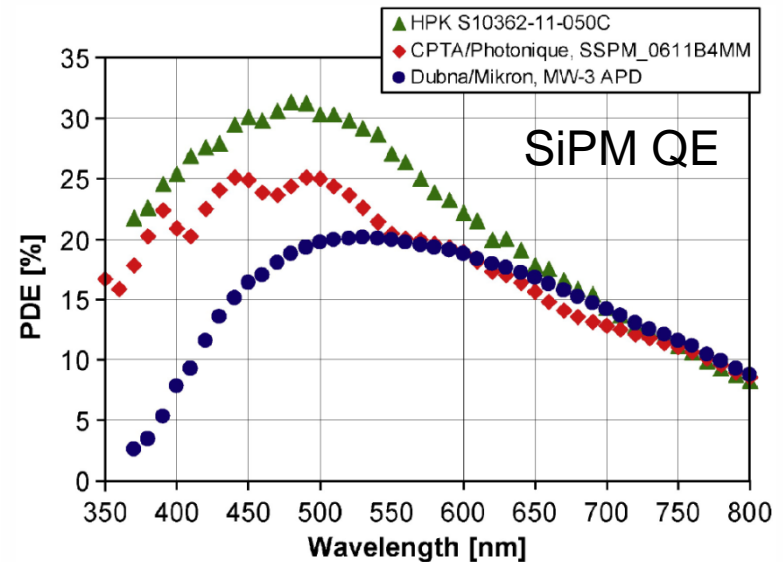
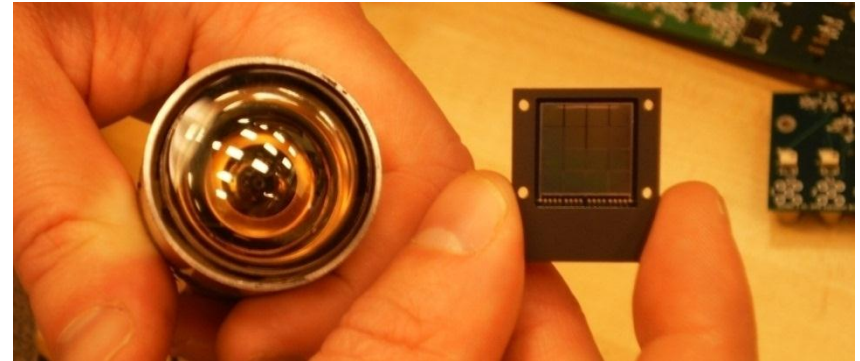
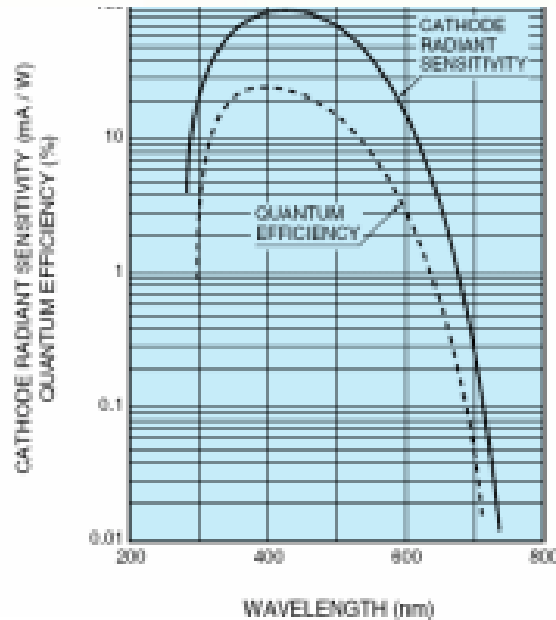
PbF₂ prototype



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Photodetector choices: SiPM vs PMT

Hamamatsu R9800



$$\text{PDE} = \text{QE} \times \text{avalanche prob.} \times \text{geometrical fill factor}$$

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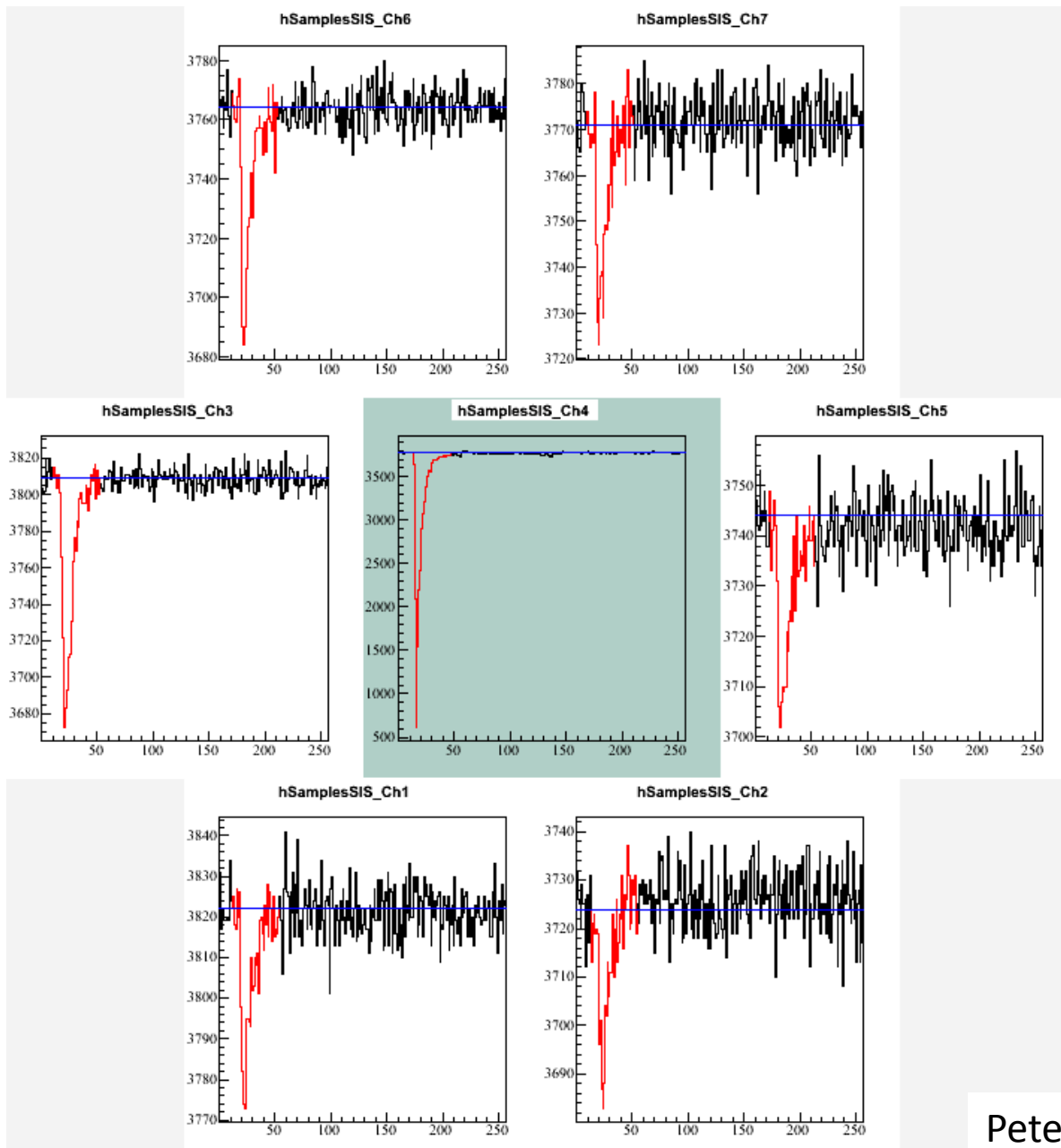
David Hitlin

PXPS EM Calorimetry Summary

June 2012

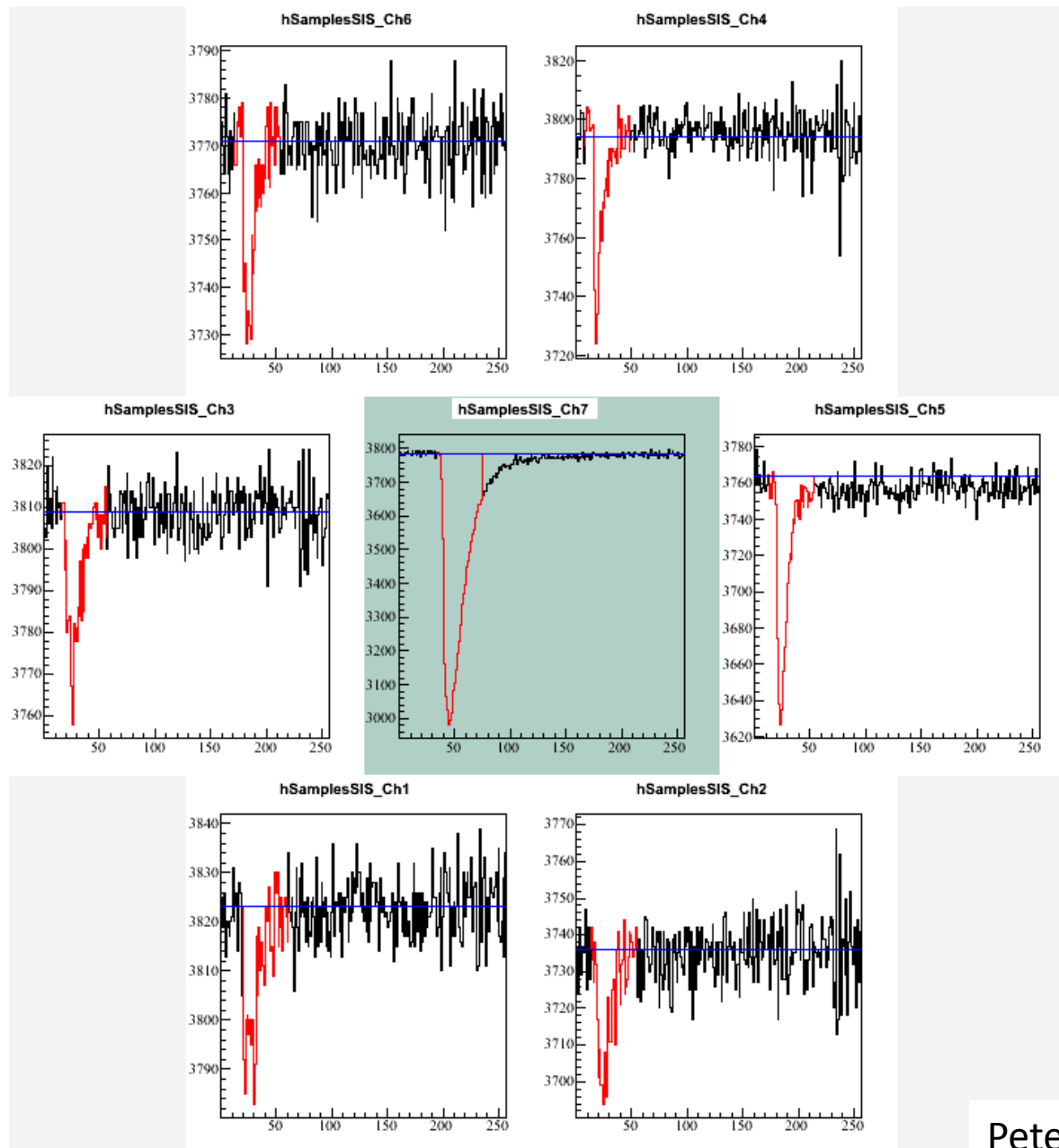
40





Peter Winter

Struck digitizer: 500 MHz, 8bit



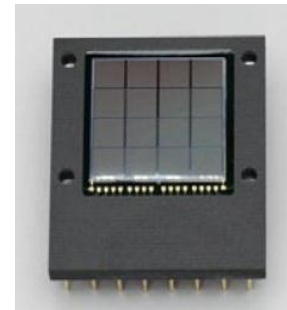
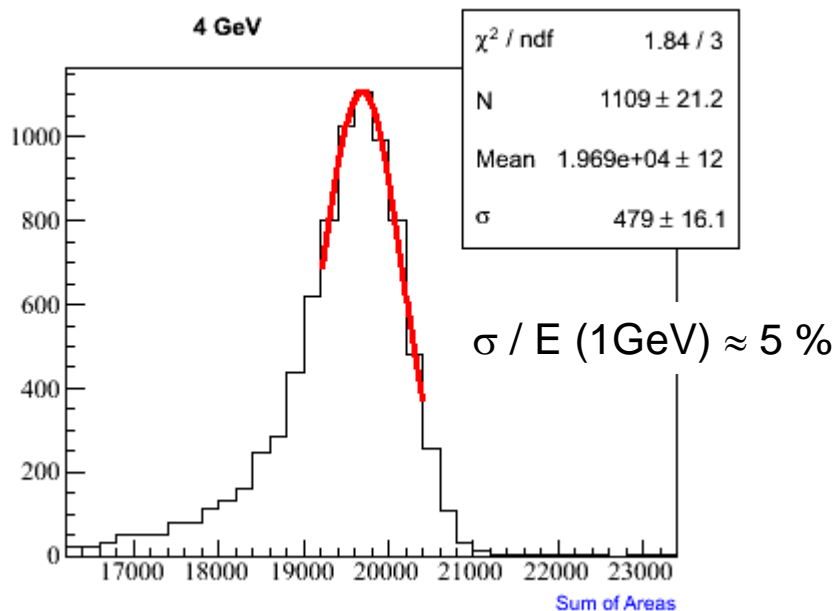
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SiPM and employed electronics not optimized for signal duration in this test!

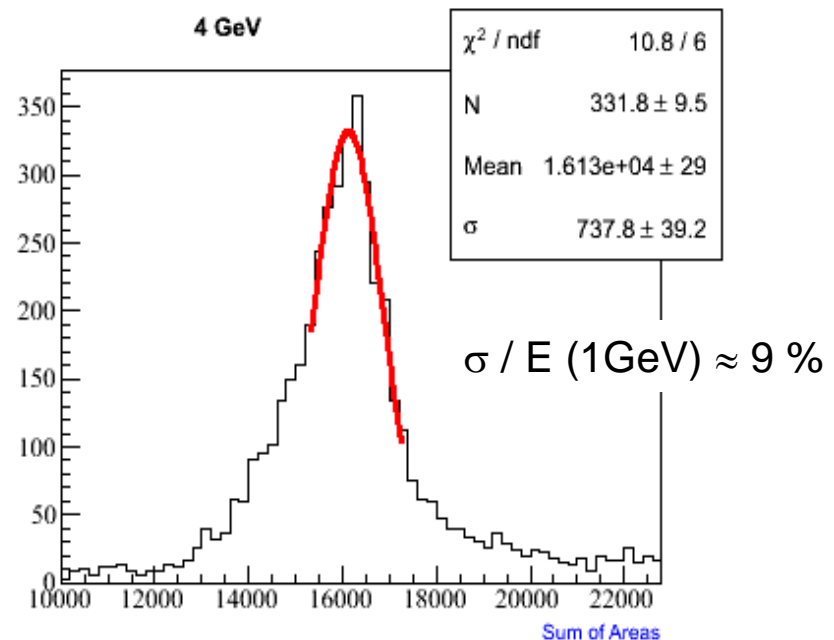
Light yield at 4 GeV



Active area: 500 mm²



Active area: 90 mm²



Peter Winter



Kaon experiments

- Laurie Littenberg and Andrei Poblaguev discussed KOPIO
 - π^0 detection with a preradiator and a shashlyk calorimeter
- Corrado Gatto and Anna Mazzacane discussed ORKA
 - Shashlyk and ADRIANO options
- Elizabeth Worcester discussed the KTeV calorimeter in detail



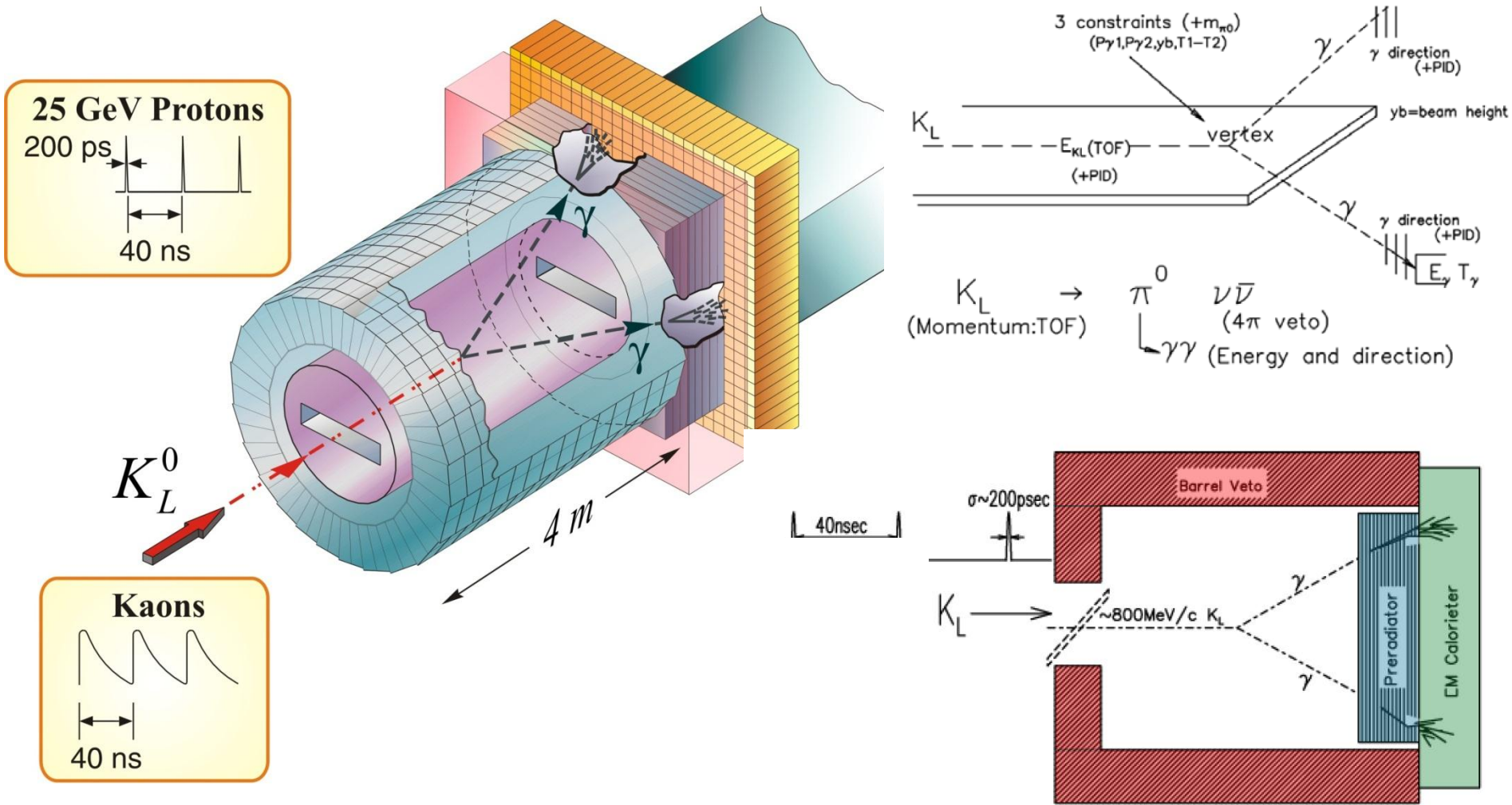
The Challenge of KOPIO

- “Nothing in – Nothing out”
- $B(K_L \rightarrow \pi^0 \nu \nu) \sim 3 \times 10^{-11} \Rightarrow$ need huge flux of K 's
 - rates inevitably rather high
- Kinematic signature weak (2 particles undetectable)
- π^0 - related backgrounds with up to 10^{10} times larger
- Veto inefficiency on extra particles must be $\leq 10^{-4}$
- Huge flux of neutrons in beam
 - can make π^0 off residual gas – require high vacuum
 - halo must be very small
 - hermeticity requires photon veto in this beam
- Need a convincing measurement of background

Laurie Littenberg



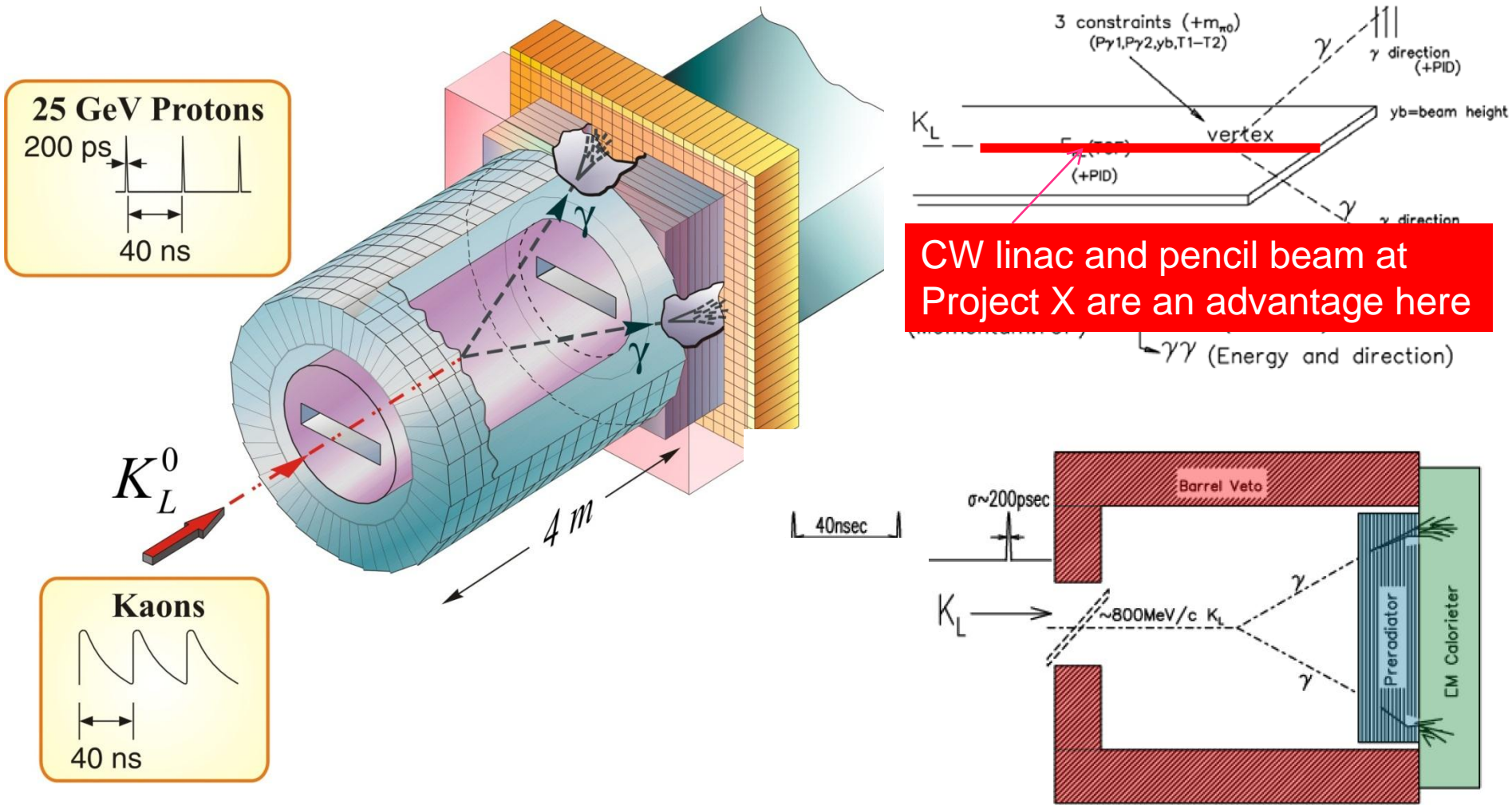
Calorimetry for a KOPIO-type experiment



Laurie Littenberg, Andrei Poblaguev



Calorimetry for a KOPIO-type experiment



Laurie Littenberg, Andrei Poblaguev



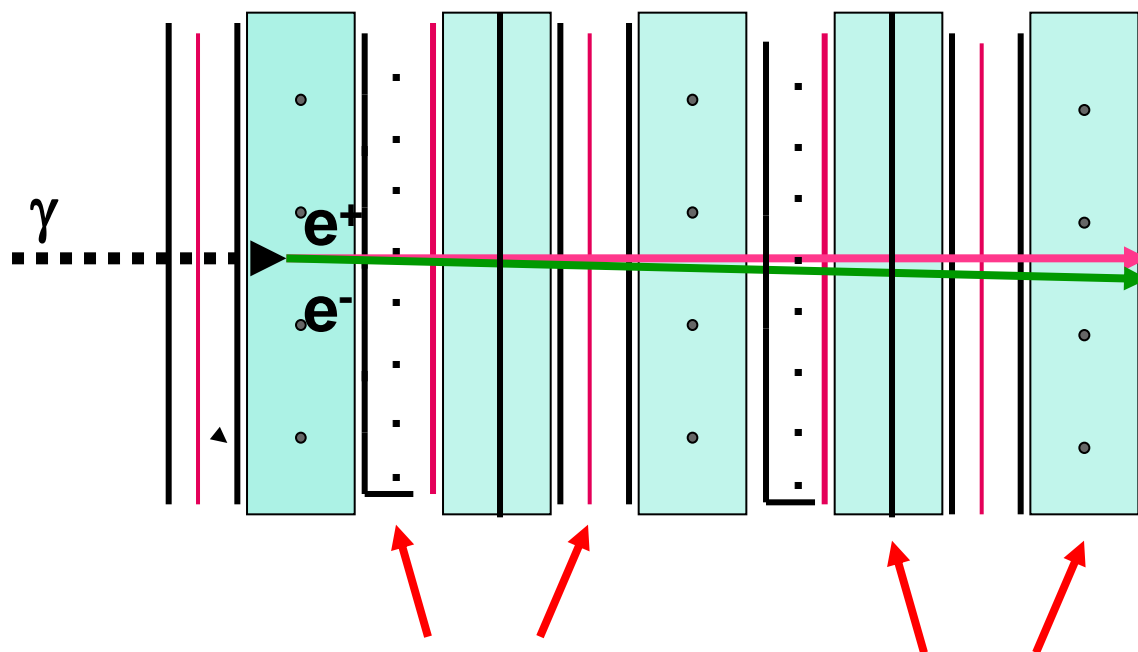
The KOPIO calorimeter challenge

- Dealing with rather low energy photons
- Must measure photon direction well
 - at least 25mr at 250MeV
- Must measure energy very well
 - at least 3%/√E
- (In the AGS version, these two functions were spread between two systems – better if one system could do both)
- Must measure time to $\sim 100\text{ps}/\sqrt{E}$
- Must serve as super-efficient veto!
 - No dead material
- Must do all this in the presence of very high rates.

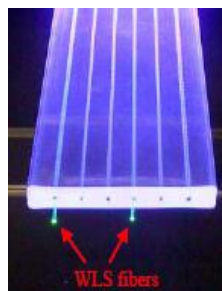
Laurie Littenberg



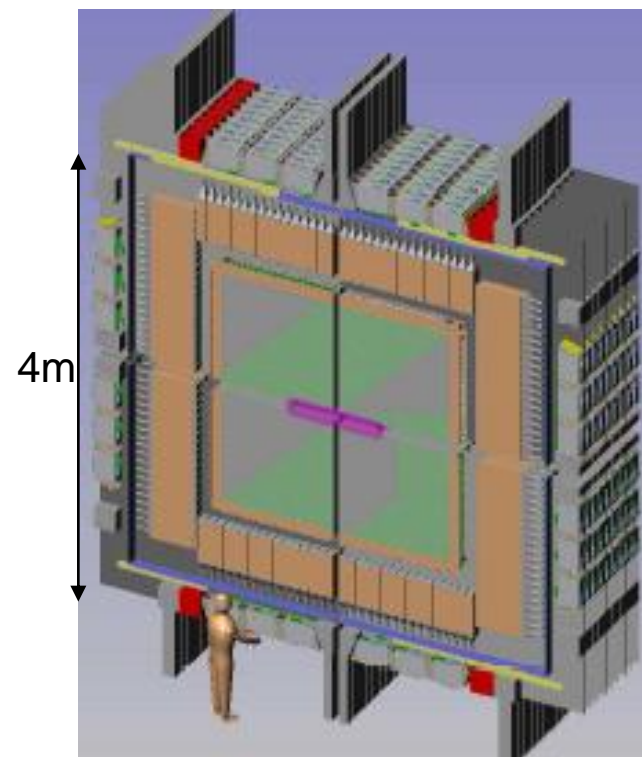
Preradiator – convert & measure γ properties



**Cathode
strip
drift
chambers**



**Extruded
Scintillator &
WLS fibers**



**64 Layers (4% X_0 /layer, 2.7
 X_0) 256 Chambers
288 Scintillator Plates (1200
 m^2) 150,000 Channels
Readout**

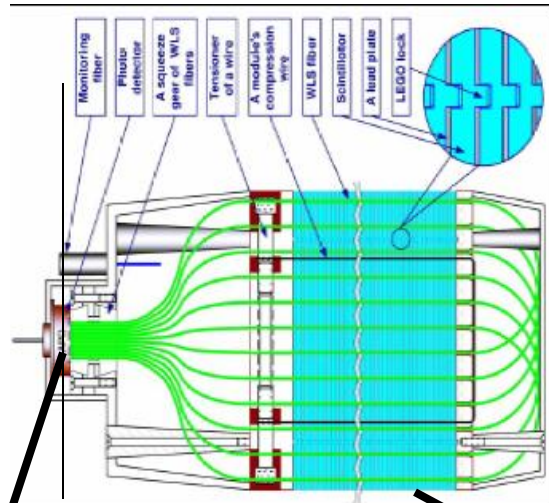
Laurie Littenberg



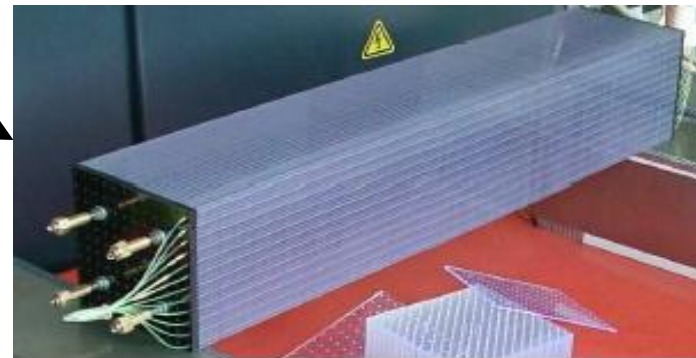
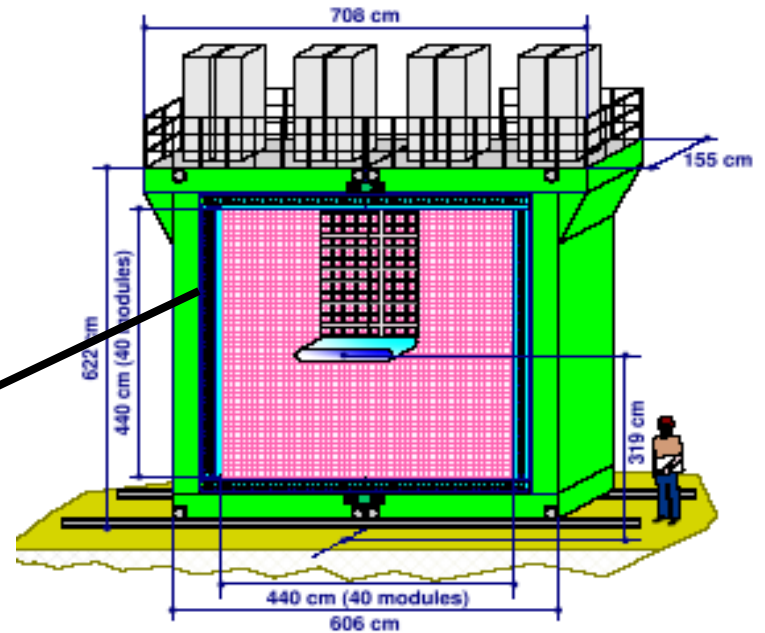
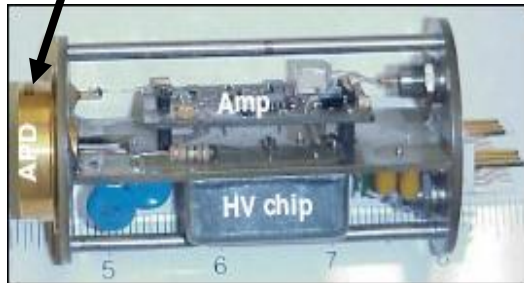
Shashlyk photon calorimeter

Shashlyk modules were prototyped
and tested in beams

All required specs were met



APD

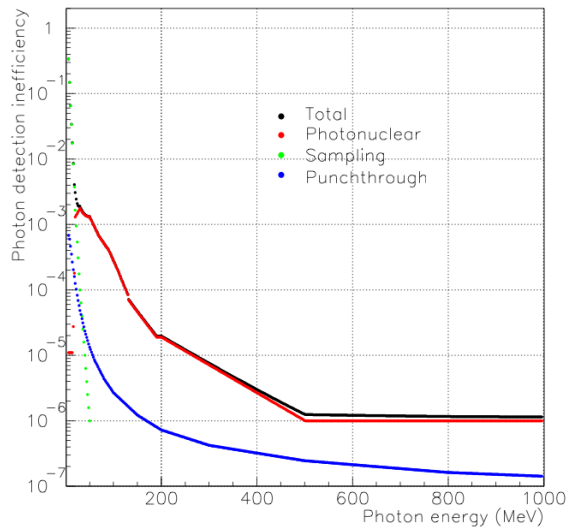


Laurie Littenberg

KOPIO specs and tradeoffs

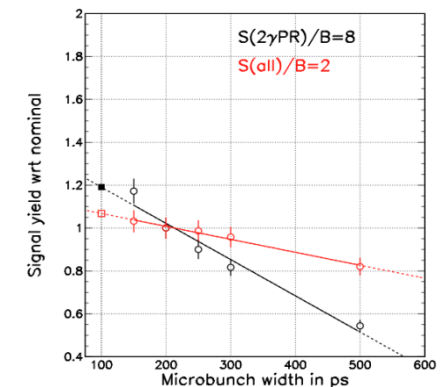
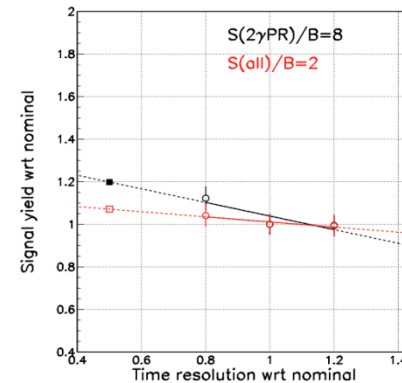
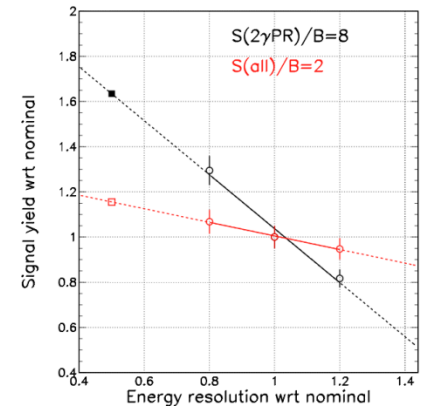
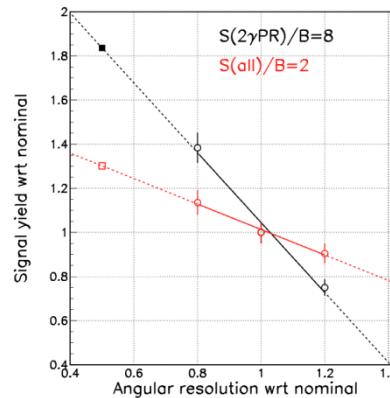
- $\sigma_E = 2.7\%/\sqrt{E}$
- $\sigma_t = 90\text{ps}/\sqrt{E}$
- $\sigma_\theta = 25\text{mr} @ 250 \text{ MeV}$
- $\sigma_{x,y} = 250\mu$
- $\sigma_\eta = 10^{-4}/\gamma$

Photon Inefficiency



1 MeV visible energy threshold
90° incidence angle

Parameter variations

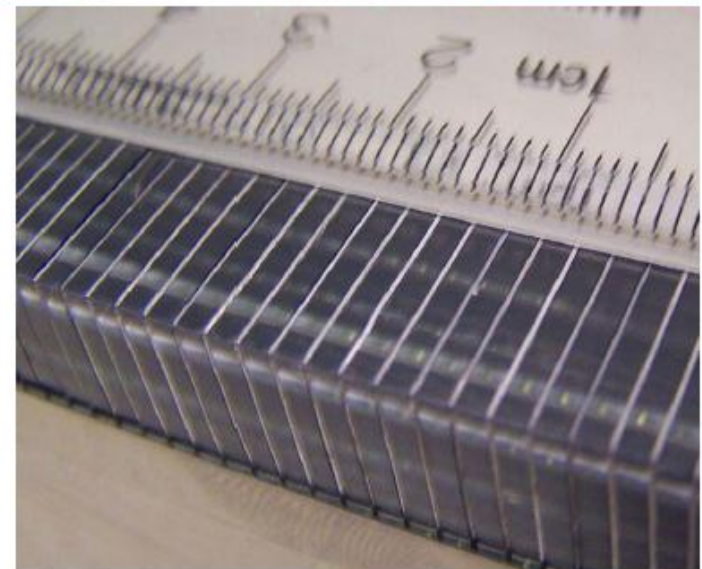
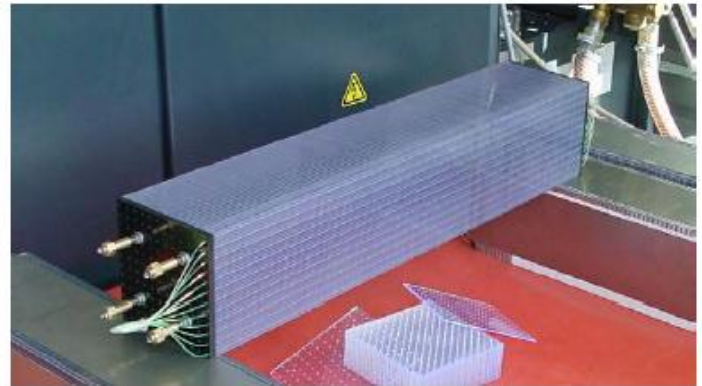


Laurie Littenberg



The $3\% / \sqrt{E}$ shashlyk module

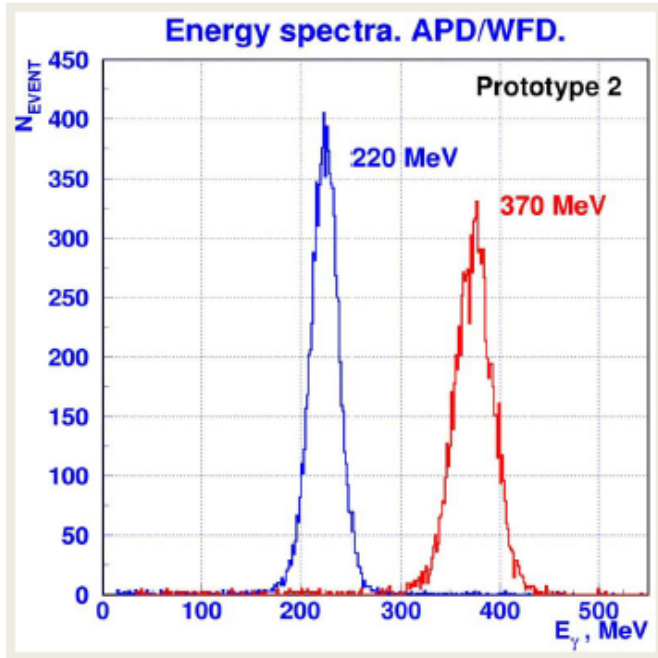
Transverse size	110×110 mm ²
Scintillator thickness	1.5 mm
Spacing between scintillator tiles	0.350 mm
Lead absorber thickness	0.275 mm
Number of the layers (Lead / Scint)	300
WLS fibers per module	$72 \times 1.5 \text{ m} = 108 \text{ m}$
Fiber spacing	9.3 mm
Holes diameter in Scintillator / Lead	1.3 mm
Diameter of WLS fiber (Y11-200MS)	1.0 mm
Fiber bundle diameter	14.0 mm
External wrapping (TYVEK paper)	150 μm
Effective X_0	34.9 mm
Effective R_M	59.8 mm
Effective density	2.75 g/cm ³
Active depth	555 mm (15.9 X_0)
Total depth (without photo-detector)	650 mm
Total weight	21.0 kG



Andrei Poblaguev

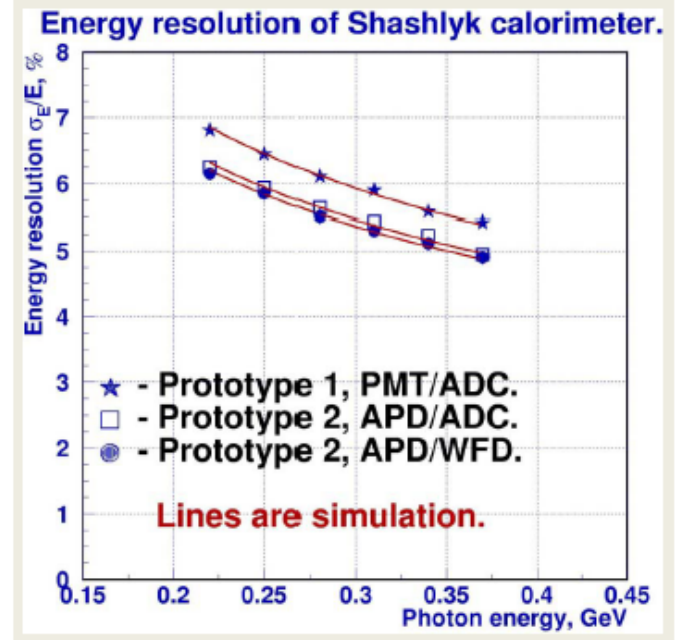


Energy resolution



Module 1	Module 2	Module 3
Module 4	Module 5	Module 6
Module 7	Module 8	Module 9

⊗ Beam (E study)



Energy resolution for 220-370 MeV photons:

$$\sigma_{\text{PMT}}/E = (2.03 \pm 0.1)\% \oplus (3.06 \pm 0.05)\%/\sqrt{E \text{ (GeV)}}$$

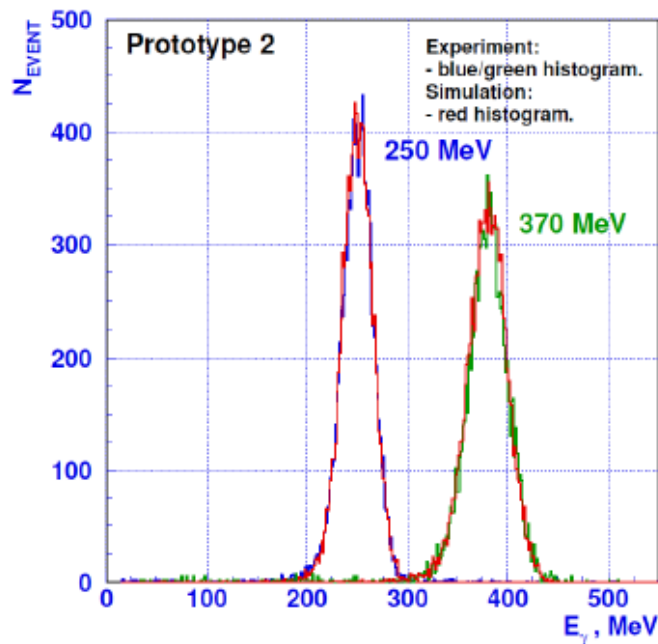
$$\sigma_{\text{APD}}^{\text{QDC}}/E = (1.98 \pm 0.1)\% \oplus (2.79 \pm 0.05)\%/\sqrt{E \text{ (GeV)}}$$

$$\sigma_{\text{APD}}^{\text{WFD}}/E = (1.96 \pm 0.1)\% \oplus (2.74 \pm 0.05)\%/\sqrt{E \text{ (GeV)}}$$

Andrei Poblaguev



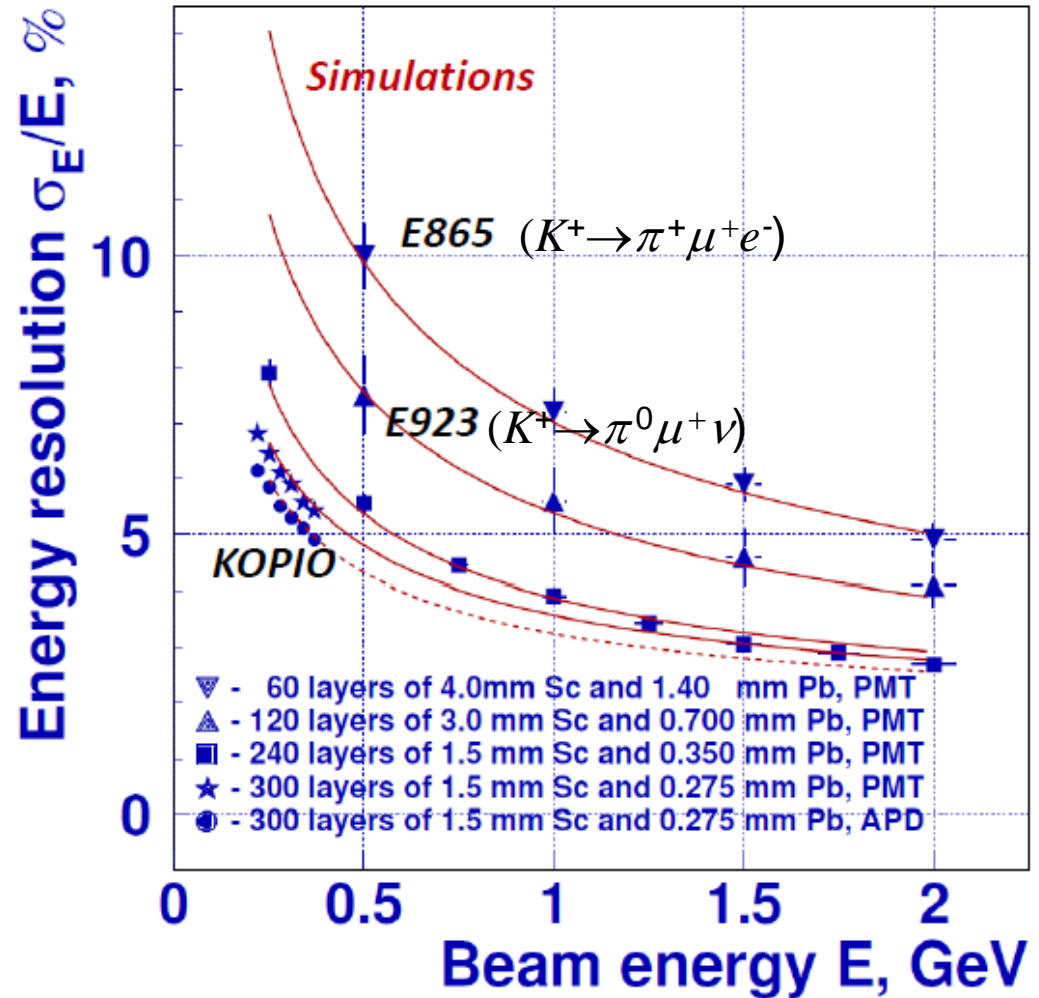
Shashlyk energy resolution: exp vs simulation



Simulation:

Geant 3 + Optical model

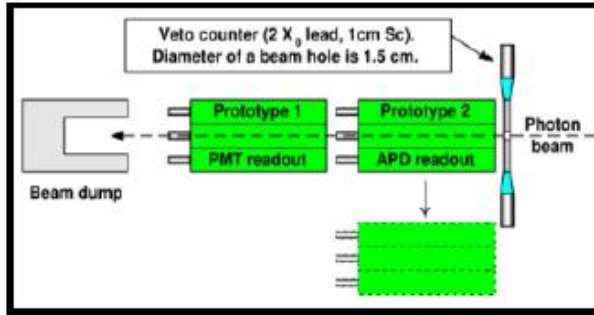
(G.S.Atoian et al, NIM A531 (2006) 467-480)



Andrei Poblaguev



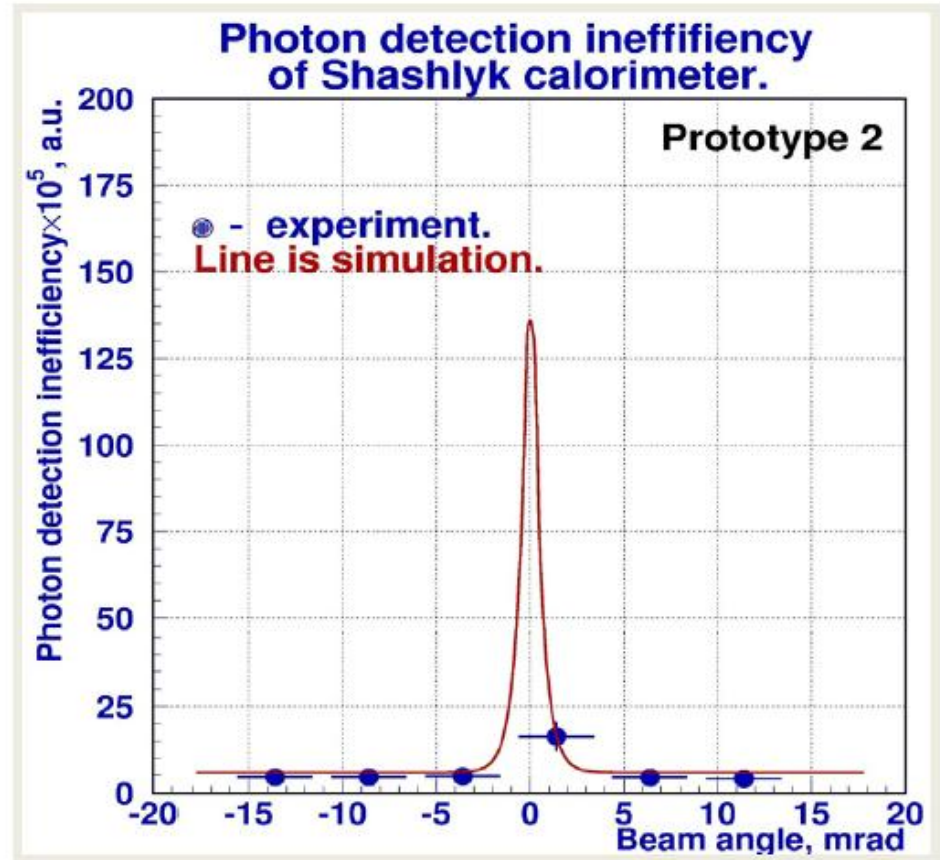
Photon detection inefficiency



Simple estimate of Inefficiency
(due to holes):

$$\sim N_f \frac{\pi r_h^2}{a^2} \frac{r_h^2}{L^2 \sigma_\theta^2}$$

$$\approx 0.02 / \sigma_\theta^2 \text{ (mrad}^2\text{)}$$



The effect of the holes is negligible if incident angle > 5 mrad

Andrei Poblaguev

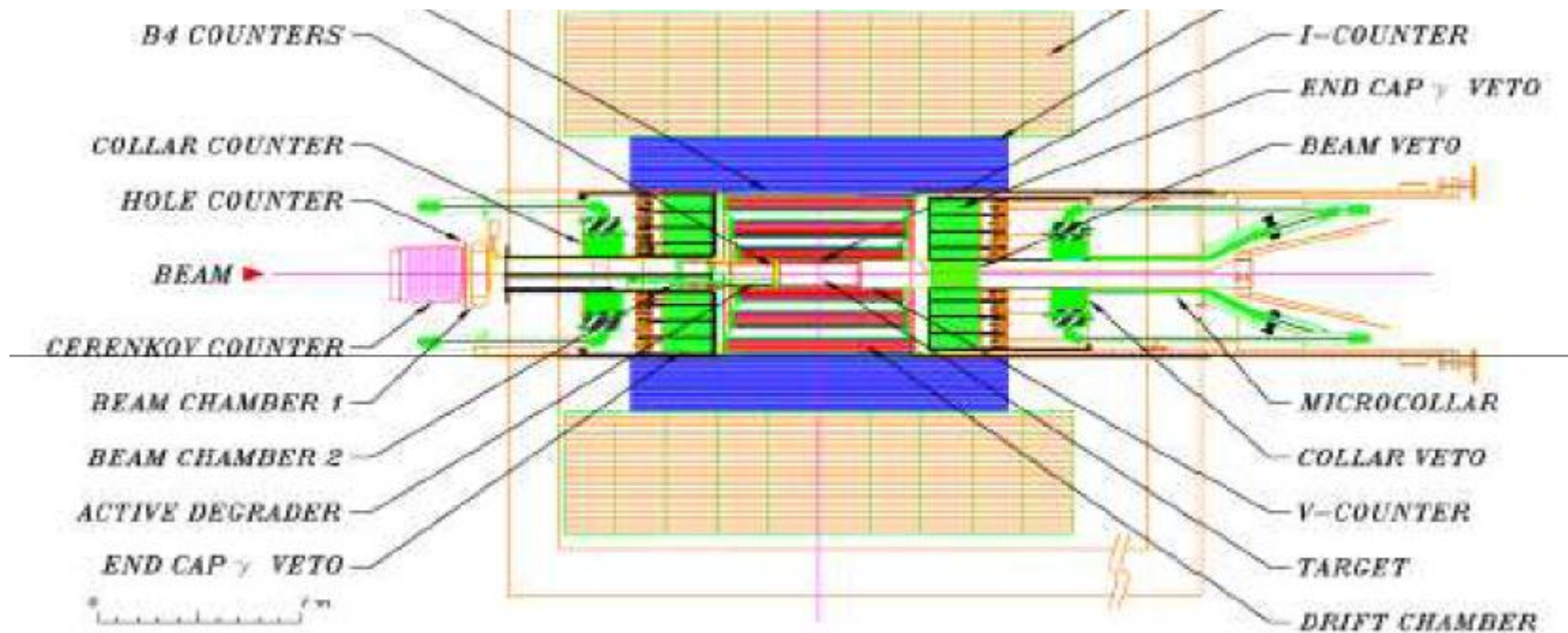


Coda on calorimetry for $K^+ \rightarrow \pi^+ \nu \nu$

- Situation is much different – **signal** is not photons!
- Emphasis on vetoing – need similar vetoing as in neutral mode, but can afford to sacrifice everything else to it
 - *i.e.* no need to accurately determine the direction of the photons
 - resolution not crucial except insofar it is correlated with efficiency
- Photon analysis important in “other” physics queries
 - Note that the stopping geometry is an impediment in many otherwise appealing processes.
 - Acceptance tends to be a strong function of energy for charged particles
 - The stopping target presents unavoidable material
 - RS forces non-uniform nature of photon detection.
- Be good if the whole detector was part of the calorimetry



ORKA calorimeter schematic



- **Barrel technology:** Shashlyk/ADRIANO
- **Barrel:** $R_{in} - R_{out} - L$ 70:145:240 cm³
- **Barrel Weight:** 25-30 ton
- **Barrel segmentation:** 385 towers 32x25 cm² or 32-64 wedges

- **Endcap technology:** Csl (undoped)
- **Endcap size:** dia:L: 98cm:25cm
- **Endcap Weight:** 1.13 ton
- **Endcap segmentation:** 24 6x5x25 cm³ + 119 8.5x7-8x25 cm³

75 kW

Corrado Gatto



ORKA calorimeter requirements

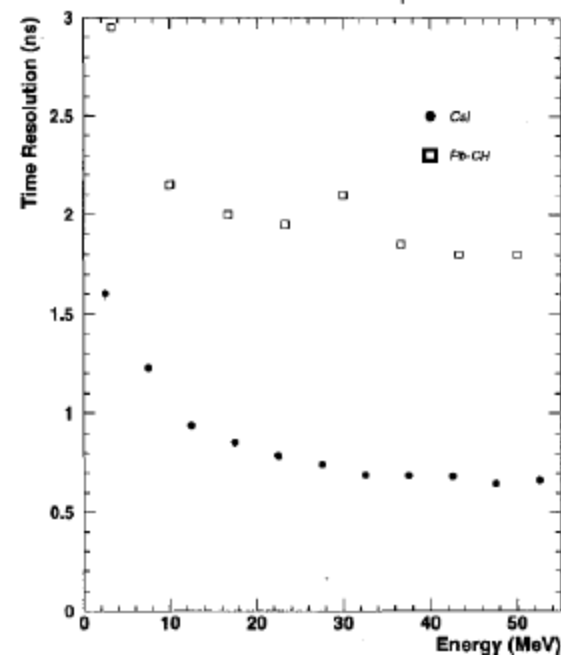
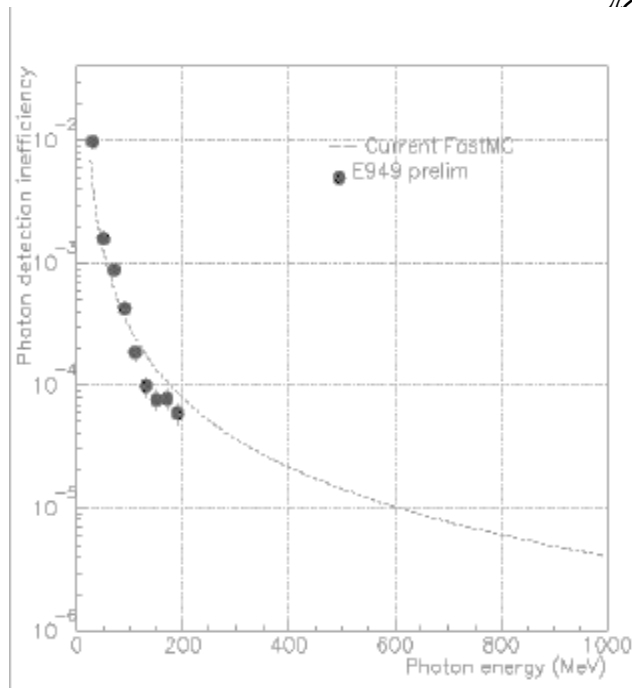
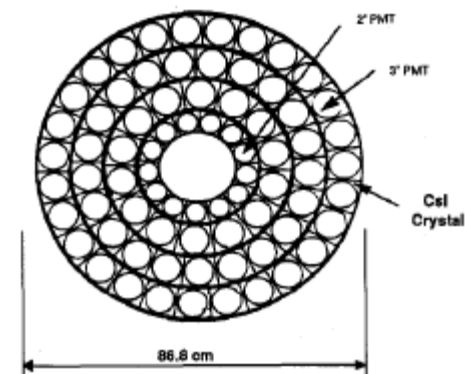
- π^0 rejection $> 10^6$ - 10^7
 - $\Rightarrow \gamma$ inefficiency $< 10^{-3}$ - 10^{-4} above 20 MeV for angles $90^\circ - 20^\circ$
 - Sensitivity down to a few MeV
 - Depth $> 20 X_0$
 - Accidentals rate: 0.011/MHz (to keep same accidental rate as E949)
 - Max scintillator decay time: 8 ns
 - Energy resolution 10-15% @ 200 MeV (from E949 – study needed)
 - γ/n discrimination desirable
- Light yield ~ 1 pe/MeV
- $X_0 < 3\text{cm}$; $\langle \rho \rangle > 3$ g/cc
- Energy threshold chosen as a compromise between low inefficiency and low accidental rate
- Inorganic scintillator and/or Cerenkov radiator
- Dual readout calorimetry

Corrado Gatto



ORKA endcap calorimeter

- Re-use E949 endcap calorimeter
- 25 cm undoped CsI crystals
 - 13.5 X_0 (may not suffice for ORKA)
 - 10 ns decay time (+slow component)
 - $\Delta E/E = 10.6\%$ for π^0 from $K_{\pi 2}$ decays (245.6 MeV)



Corrado Gatto



ORKA candidate barrel calorimeter technologies

Shashlyk

• Pro

- Cheap
- Well established technology
- Extensive test beam

• Cons

- Sampling fluctuations
- Inadequate for $E_\gamma < 50$ MeV
- Large inefficiency for low energy photon

ADRIANO with heavy glass or PbF_2

• Pro

- Integrally active calorimeter
- Higher detection efficiency
- S vs C provides PID

• Cons

- More expensive
- Novel technology
- Tested only at high energy (500 MeV)

ADRIANO in single readout mode

• Pro

- Integrally active calorimeter
- Highest detection efficiency

• Cons

- Also expensive
- Untested technology
- No PID

PXPS, June 2012

C. Gatto - INFN Napoli

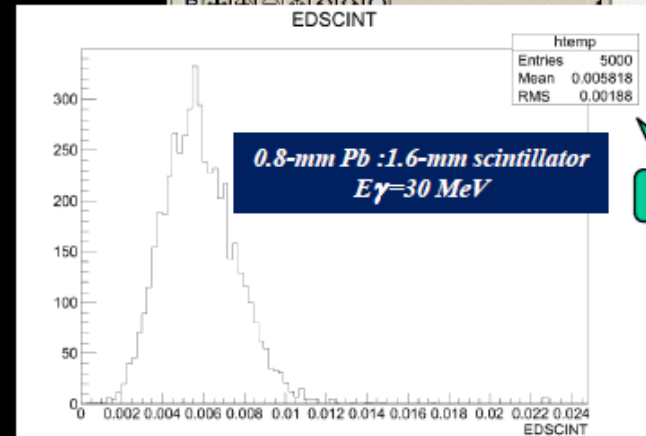
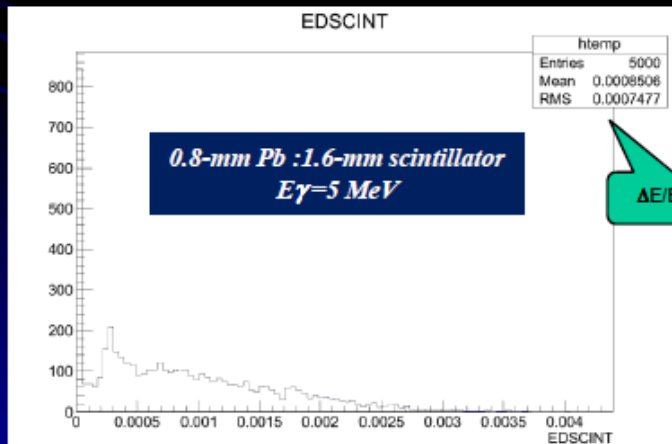
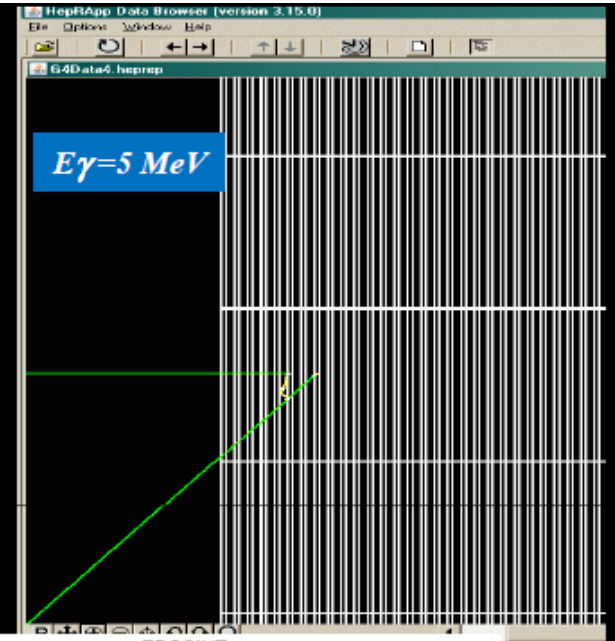
8

Corrado Gatto



Shashlyk issues

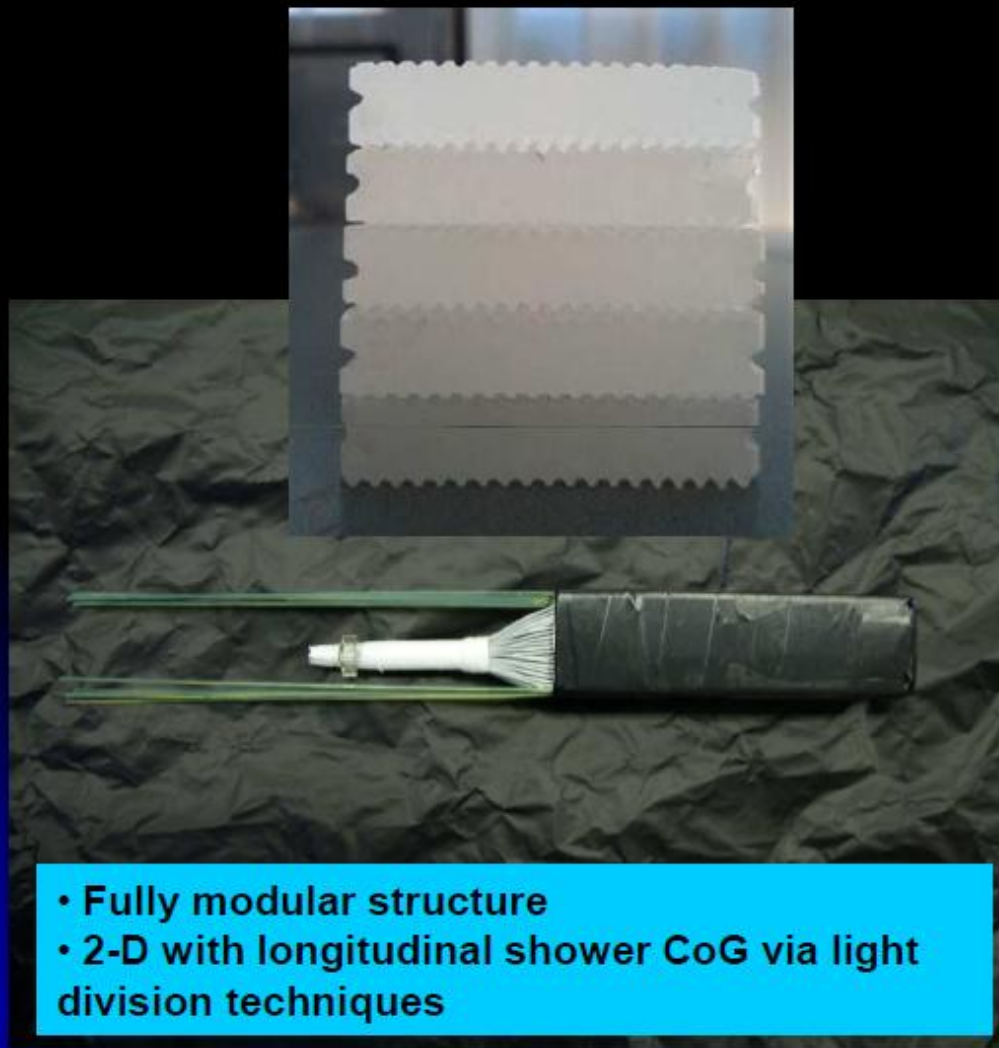
- Range of Compton e^- in Pb from low energy γ is about 0.5 mm
- Effective absorber thickness changes as $tg^{-1}\theta$ (~ 2.75 at $\theta=20^\circ$)
- WLS fibers have 1/10 light yield than scifi: potential crack from channeling in 0.9% volume (holes are 1.3 mm)
- Beam test of 300 layers of 0.275mm Pb/1.5mm scintillator
 - E_{beam} : 50-1000 MeV
 - 85% sampling fraction (rather than 33%)
 - $X_0 \sim 3.5\text{cm}$; $\langle\rho\rangle \approx 2.75\text{ gr/cm}^3$
 - Use Y11 (too slow for ORKA): expect a 30% lower l.y.
- Large sensitivity to neutrons with no PID
- Energy resolution is very poor for $E_\gamma < 20\text{ MeV}$



Corrado Gatto



ADRIANO — A Dual-Readout Integrally Active Non-segmented Option



- **Cells dimensions:** 4x4x180 cm³
- **Absorber and Cerenkov radiator:** lead glass or bismuth glass ($\rho > 5.5 \text{ gr/cm}^3$)
- **Cerenkov light collection:** 10/20 WLS fiber/cell
- **Scintillation region:** scintillating fibers, dia. 1mm, pitch 4mm (total 100/cell) optically separated from absorber
- **Particle ID:** 4 WLS fiber/cell (black painted except for foremost 20 cm)
- **Readout:** front and back SiPM (Scifi only)
- **CoG z-measurement:** light division applied to SCSF81J fibers (same as CMS HF)
- **Small $\text{tg}(\theta_{s/Q})$:** due to WLS running longitudinally to cell axis ($\theta_{\text{Cerenkov}} < \theta_{\text{Snell}}$ for slower hadrons).

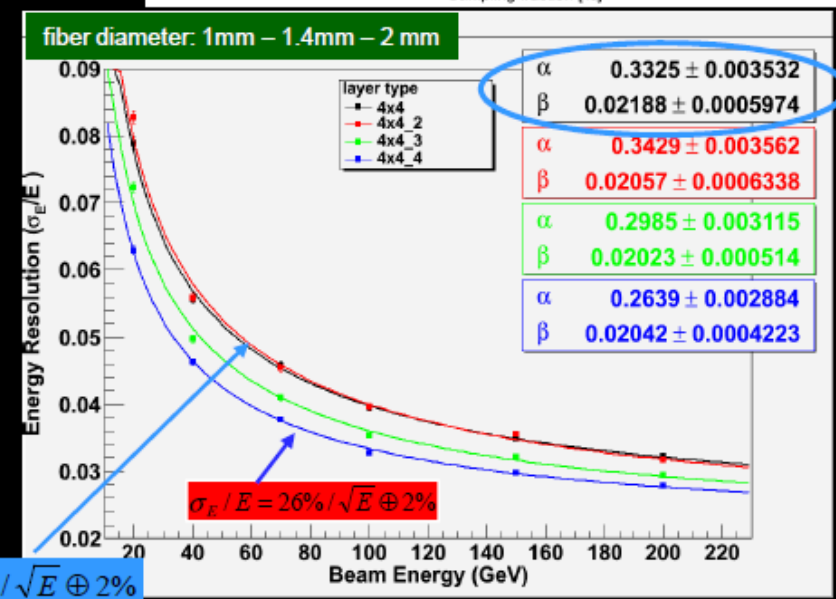
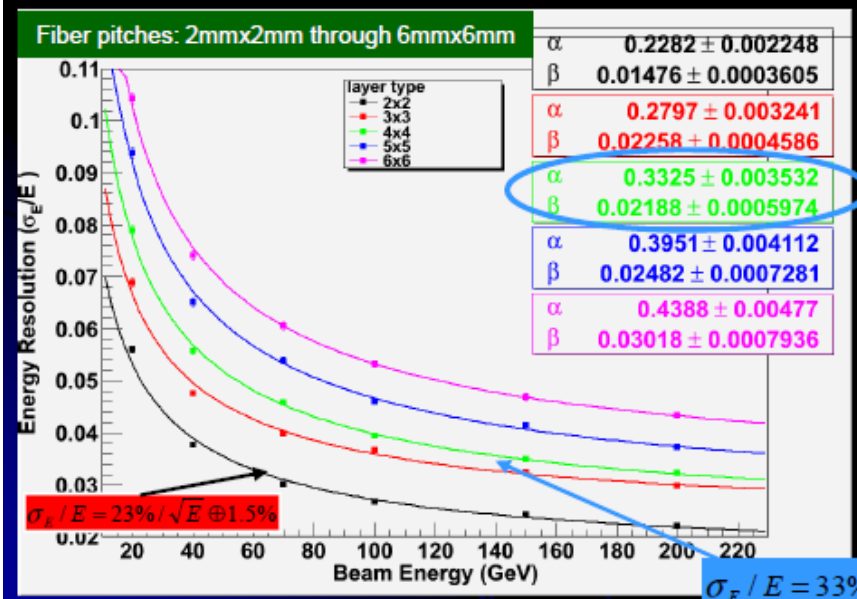
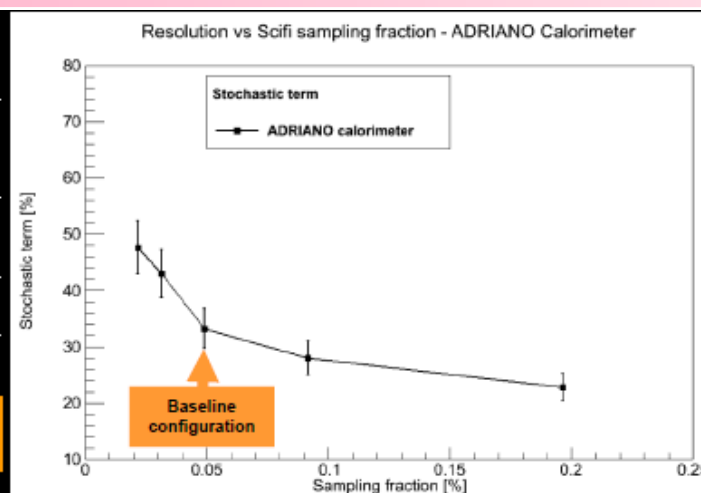
Corrado Gatto

ADRIANO light yield and hadronic resolution

Integrally Active with Double side readout (ADRIANO)									Sampling
Pitch [mm ²] Diameter	2x2 1mm	3x3 1mm	4x4 1mm	5x5 1mm	6x6 1mm	4x4 1.4mm	4x4 2mm	4x4 capillary	Sampling
$\langle pe_s \rangle / \text{GeV}$	1053	430	254	163	124	500	110	250	200
$\langle pe_c \rangle / \text{GeV}$	340	360	360	355	355	355	350	350	7.5

Baseline
configuration

1-side
readout



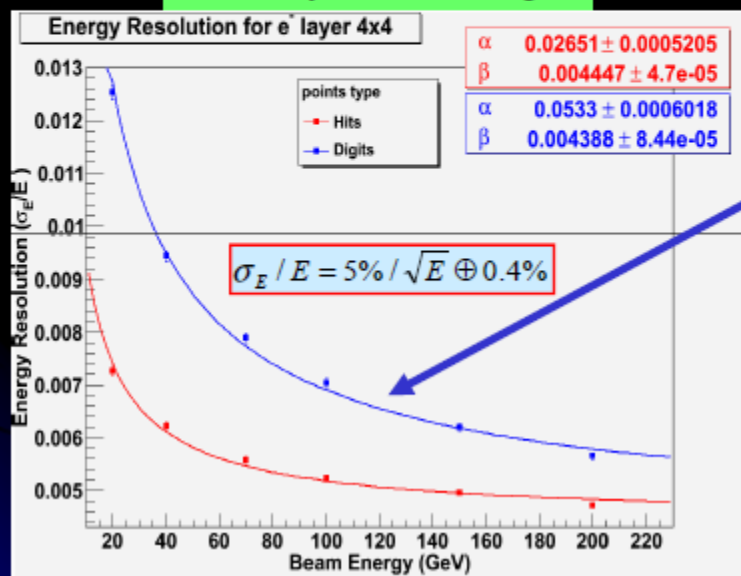
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ADRIANO EM resolution

- Compare standard Dual-readout method vs Cerenkov signal only (after electron-ID)
- Blue curve includes instrumental effects. Red curve is for perfect readout

Use only Cerenkov light

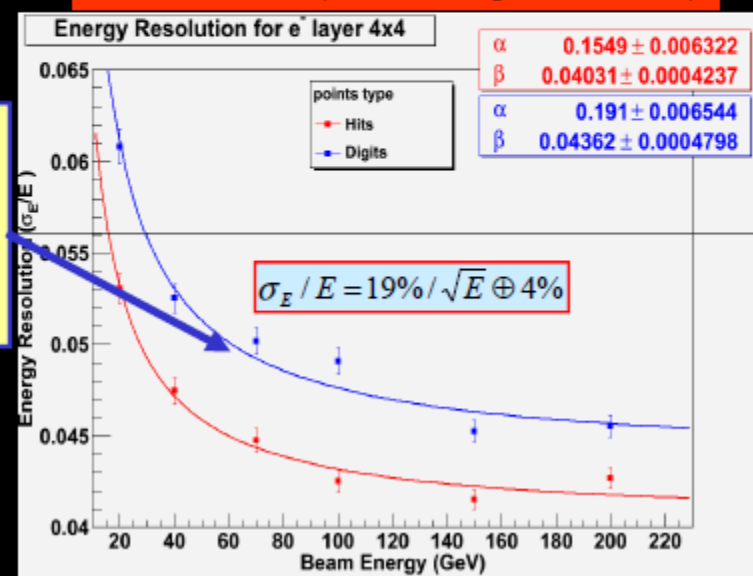


Blue curve includes:

- SiPM's ENF
- Constant noise
- Fiber non-uniformity
- 14 bit ADC
- 3pe threshold

ILCroot simulations

Dual-readout (scintillating+Cerenkov)



Corrado Gatto



ADRIANO for ORKA baseline

- **150 layers; 2mm PBH56/SF57 + 2mm fast scintillator (BC408 or SN88)**
 - $X_0 = 2.9 \text{ cm}$; $\langle \rho \rangle = 3.5 \text{ gr/cm}^3$; Depth = $21 X_0$
- **Detector layout: 2.5m longitudinal layers with 2-sides readout in 64 azimuthal sectors (E949/KLOE approach)**
 - $5.6^\circ/\text{sector}$; 9.5-13.5 cm sector width
 - Towers with back readout also considered, but potentially inefficient
- **Scintillator readout; 1mm BCF92 in grooves 1.6 cm apart**
 - $\lambda(\text{BCF92}) = 350 \text{ cm}$; 1000 fibers/sector bundle in 10 units
- **Glass readout; 1mm BCF92 in grooves 1.6 cm apart**
 - $\lambda(\text{BCF92}) = 350 \text{ cm}$; 1000 fibers/sector bundle in 10 units
- **Total density of fibers: $3.1/\text{cm}^2$**
 - Compare to original ADRIANO: 6.2 fibers.cm^2

Needs
Optimization
For ORKA



Pb glass vs. PbF_2

	Glass	Crystals
Light production mechanism	Only Cerenkov (minor fluorescence with some SF glasses)	Cerenkov + scintillation
Stability vs ambiental (temperature, humidity, etc)	Excellent	Poor
Stability vs purity	Very good if optical transmittance is OK	Very poor
Longitudinal size	Up to 2m	20-30 cm max
Cost	0.8 EUR/cm ³	10-100 EUR/ cm ³
Time response	prompt	Slow to very slow (with exceptions)
n_d	1.85-2.0 (commercially available) 2.25 (experimental)	1.85-2.3
Density	6.6 gr/cm ³ (commercially available) 7.5 gr/cm ³ (experimental)	Up to 8-9 gr/cm ³
Radiation hardness	Medium (recoverable via UV annealing for Pb-glass) or unknown (for Bi-glass)	varies

Corrado Gatto



Overcoming limitations of a 2D calorimeter

- **ADRIANO for ORKA is a 2-D calorimeter**

- Easier to build and to calibrate
- Fewer number of channels
- No cracks nor unhomogeneities due to longitudinal segmentation

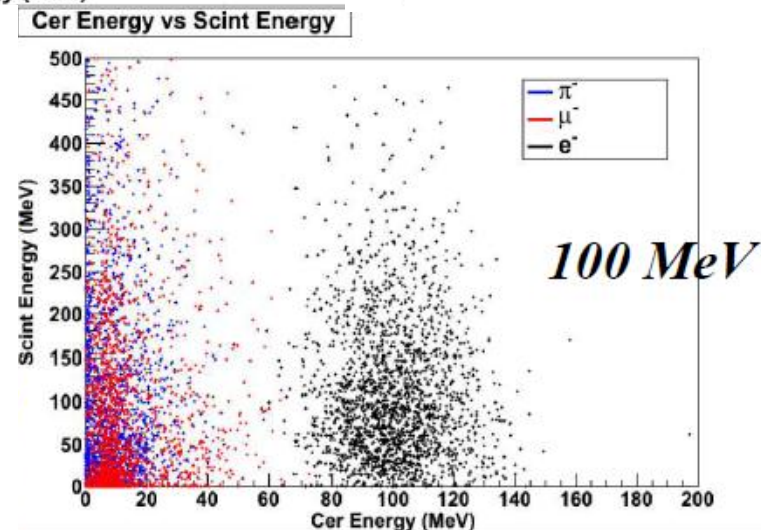
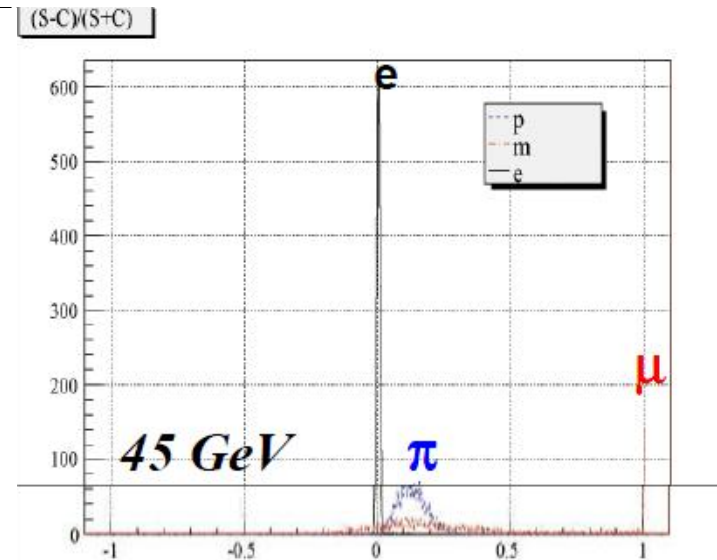
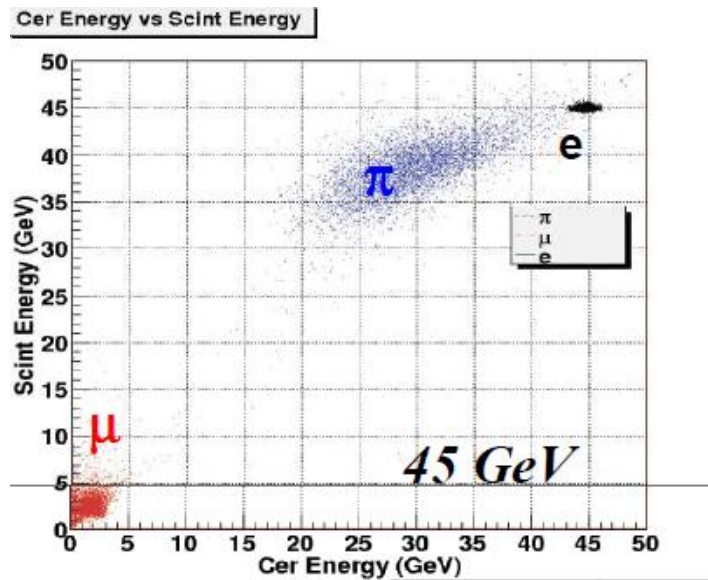
However, in principle, it misses the ability to determine the longitudinal shower profile

- ***Two possible solutions to measure z-coordinate***

- Time difference measurement
- Light division measurement



PID in a dual readout calorimeter



Corrado Gatto



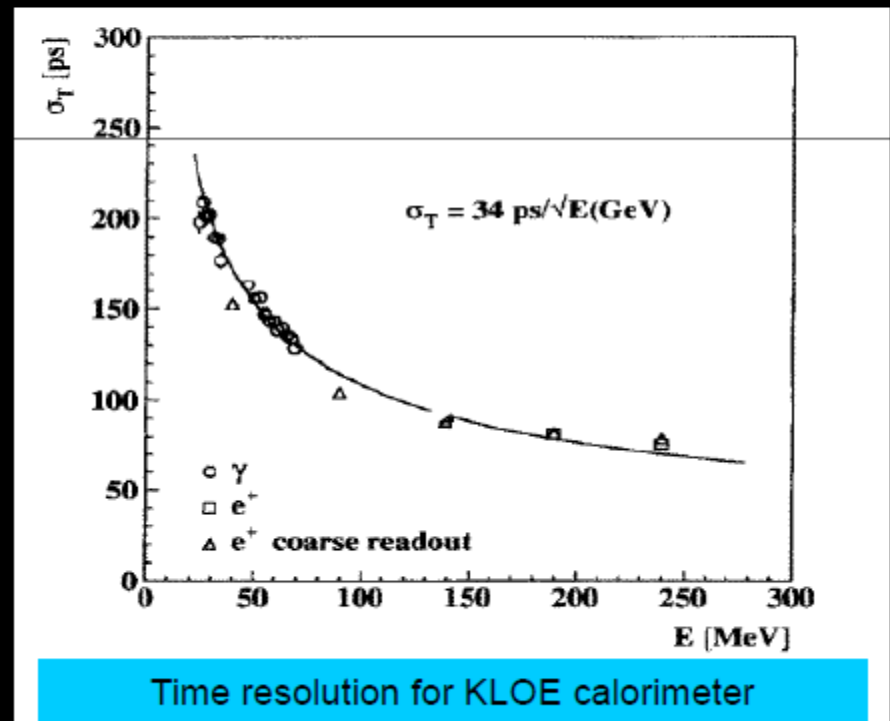
Adding the 3rd dimension with time division

- Already implemented for KLOE spcal (4.3m long, 0.5mm Pb, 15% sampling)
- Requires 25psec time measurement on both sides (TDC/WFD)
- Assume (pessimistically) the same resolution as KLOE and $v_{\text{fiber}}=17.2$ cm/nsec (for polystyrene with $n_D=1.58$)

$$\sigma_z = \frac{6 \text{ mm}}{\sqrt{E}}$$

- Or: $\sigma_z = 19$ mm at 100 MeV
- Requires z-dependent time measurement corrections:

$$\sigma_T(z) = \sigma_T(0) \sqrt{\cosh(z/\lambda)}$$



J. Lee-Franzini et al. / Nucl. Instr. and Meth. in Phys. Res. A 360 (1995) 201–205

Corrado Gatto



Adding the 3rd dimension with light division

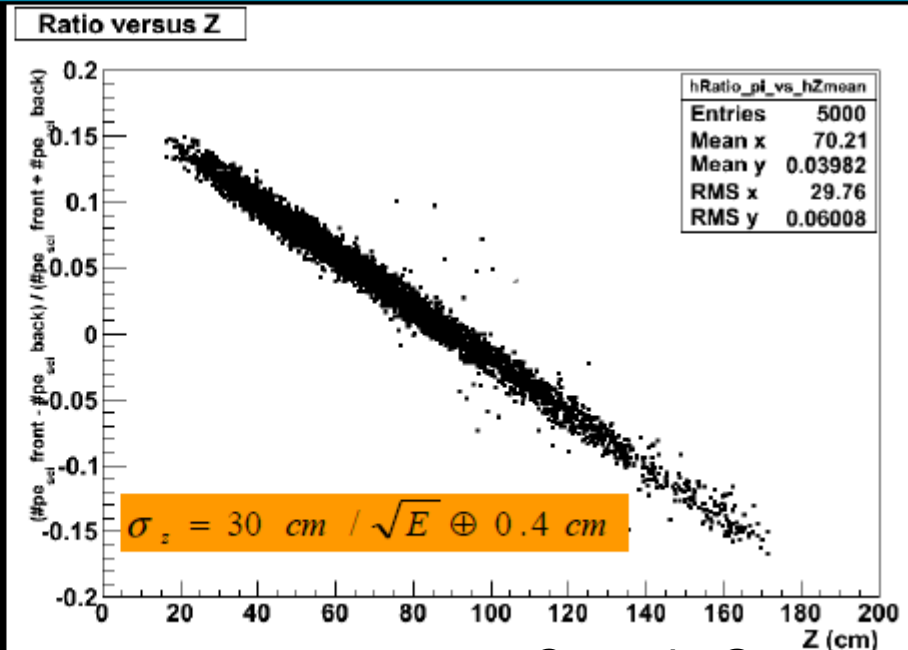
- Determine Center of Gravity of showers by ratio of front vs back scintillation light
- It works because $\lambda_{81J} = 3.5\text{m}$
- Similar to charge division methods in drift chambers with resistive wires
- A technique already adopted by UA1 and ZEUS

100 GeV pions

Instrumental effects included in ILCroot :

- SiPM with ENF=1.016
- Fiber non-uniformity response = 0.6% (scaled from CHORUS)
- Threshold = 3 pe (SiPM dark current < 50 kHz)
- ADC with 14 bits
- Constant 1 pe noise.

Front vs back Scintillation light vs true shower CoG



Corrado Gatto



Fabrication technology

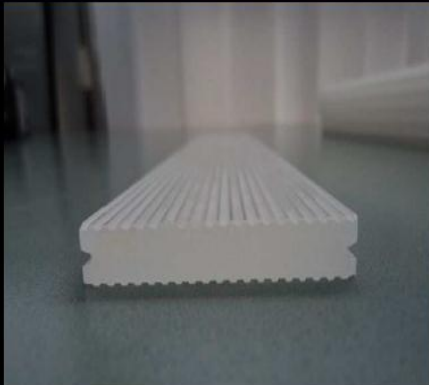
Diamond machining

- **Pro**

- Minimal R&D required
- Room temp (min effect on n_D)
- It allows construction of longer cells

- **Cons**

- Longer fabrication process
- Large waste



Precision molding

- **Pro**

- Cheapest and fastest (15 min)
- Optical finishing with no extra steps
- Low temp cycle (min effect on n_D)

- **Cons**

- Molds are expensive
- Lots of R&D



Corrado Gatto



ORKA calorimeter conclusions

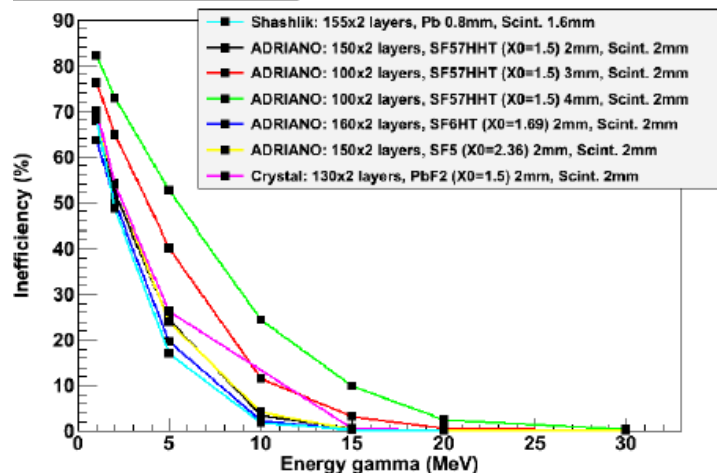
- *Three techniques are under consideration for a photon veto/calorimeter at ORKA: 1 sampling and two integrally active*
- *r-segmentation is preferred. Could switch to z-segmentation if light propagation time becomes an issue*
- **An integrally active calorimeter will easily provide at least 50% more light yield**
- Thin glass/crystals are employed as active absorber: require specific R&D
- R&D already under way under the auspices of T1015 collaboration (FNAL+INFN)
- ADRIANO technique already works for HEP: need dedicated optimization for lower energy experiment

Corrado Gatto

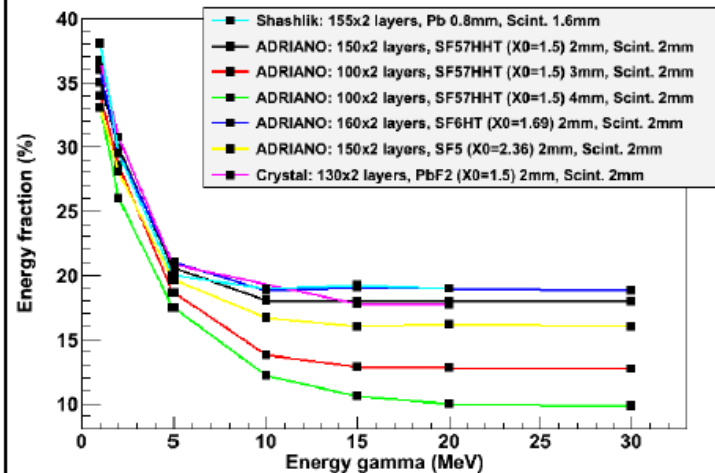


Comparison of Shashlyk and ADRIANO

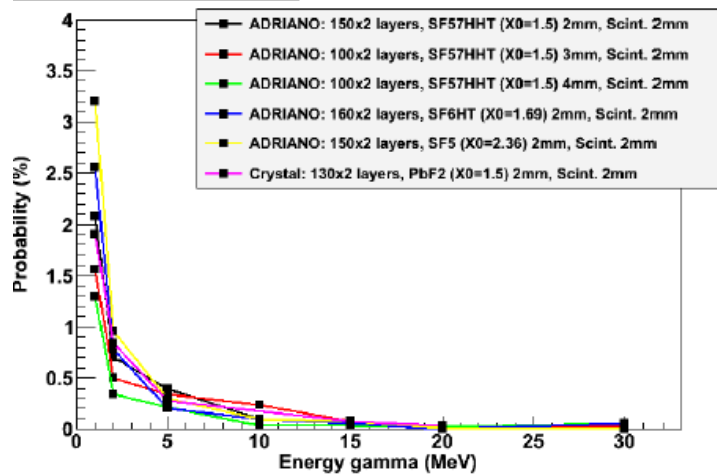
Scintillating inefficiency



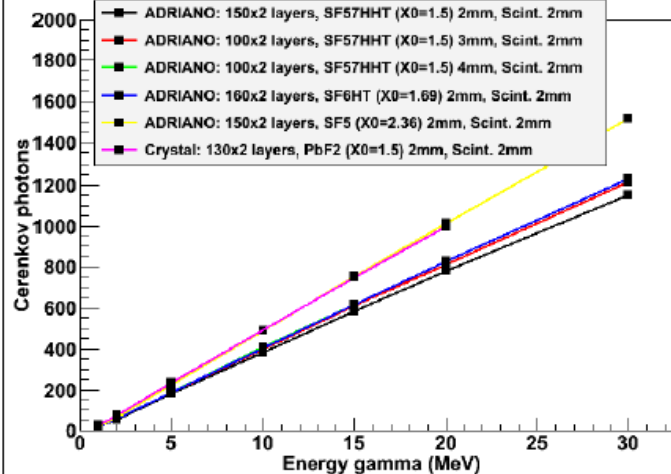
Energy fraction in Scintillator



No Cerenkov probability



Cerenkov photons



Anna Mazzacane



ORKA simulation conclusions

- I have presented very preliminary G4 simulations with 5 different layouts and materials
- Inefficiency of scintillating materials is worrisome
- Transparent materials like heavy glass or crystal may help in recovering some of these inefficiencies
- ADRIANO Cerenkov yield at high energy is 0.16 p.e./MeV
- Working on new ADRIANO layout optimized for ORKA
- **Needs lot of simulations!!!!!!**



$n\bar{n}$ oscillations

Slow free neutron in vacuum with shielded zero magnetic field develops probability of transformation to antineutron as

$$P_{n \rightarrow \bar{n}} = \left(\frac{t}{\tau_{n\bar{n}}} \right)^2 \text{ where } t \text{ is neutron flight time and } \tau_{n\bar{n}} \text{ is oscillation time predicted by theory}$$

When n is transformed to antineutron, the latter will annihilate in the thin Carbon target producing a star of 5 pions (aver.) that need to be reconstructed to the annihilation point.

anti-n + p

$\pi^+\pi^0$	1%
$\pi^+\pi^0\pi^0$	8%
$\pi^+\pi^0\pi^0\pi^0$	10%
$\pi^+\pi^+\pi^-\pi^0$	22%
$2\pi^+\pi^-2\pi^0$	36%
$2\pi^+\pi^-\omega$	16%
$3\pi^+2\pi^-\pi^0$	7%

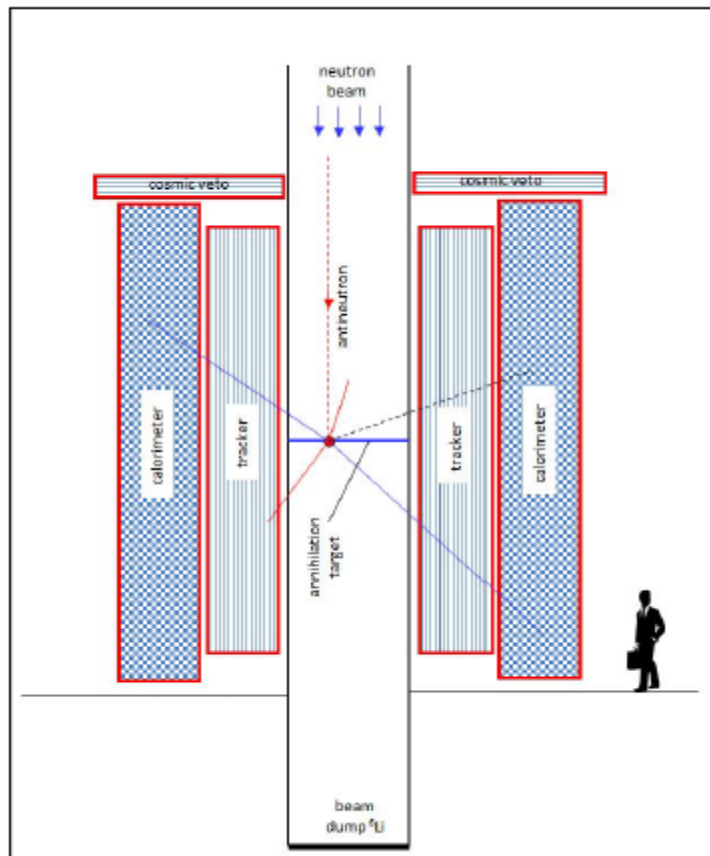
anti-n + n

$\pi^+\pi^-$	2%
$\pi^0\pi^0$	1.52%
$\pi^+\pi^-\pi^0$	6.48%
$\pi^+\pi^-\pi^0\pi^0$	11%
$\pi^+\pi^-\pi^0\pi^0\pi^0$	28%
$2\pi^+2\pi^-$	7%
$2\pi^+2\pi^-\pi^0$	24%
$\pi^+\pi^-\omega$	10%
$2\pi^+2\pi^-\pi^0\pi^0$	10%

Yuri Kamyshev



Annihilation detector for $n\bar{n}X$



Annihilation feature: $\bar{n} + C \rightarrow \langle 5\pi \rangle$

- Use ideas of backgroundless ILL detector;
- That can be Vertical and Horizontal;
- Tracker for vertex to thin carbon target;
- Calorimeter for trigger and energy reco;
- TOF before and after tracker to remove vertices of particles coming from outside;
- Veto system to suppress cosmic bkgr;
- Trigger: Calorimeter · TOF · VETO
- Shielding to minimize (n,γ) emission.

Conclusions

- There is no “perfect high energy photon detector”
- Differing requirements of individual experiments mandate experiment-specific development
 - A foundation of generic R&D, initiated sufficiently ahead of specific applications to bear fruit, can prove very useful in broadening choices and optimizing configurations
- Some generic observations
 - Experiments planned for the coming decade can typically exploit reasonable extensions of known technology for their calorimeters
 - Some R&D will be required for certain calorimeters to function at Project X Stage 1
 - At full Project X intensities, it may be necessary to fundamentally rethink experimental configurations
 - Extrapolations of known technologies may or may not be *apropos*



Conclusions II

- It is likely that several proposals for both experiment-specific and generic calorimeter R&D will emerge from these activities
- Discussions with Glen Crawford on Wednesday clarified the R&D situation somewhat (labs vs. new FOA for universities, both in KA15), but we need to understand a bit more to be able to move forward in a manner responsive to Program Office priorities
 - LOIs (strongly encouraged) – July 16 5:00PM EDT
 - Proposals – September 10 11:59PM EDT

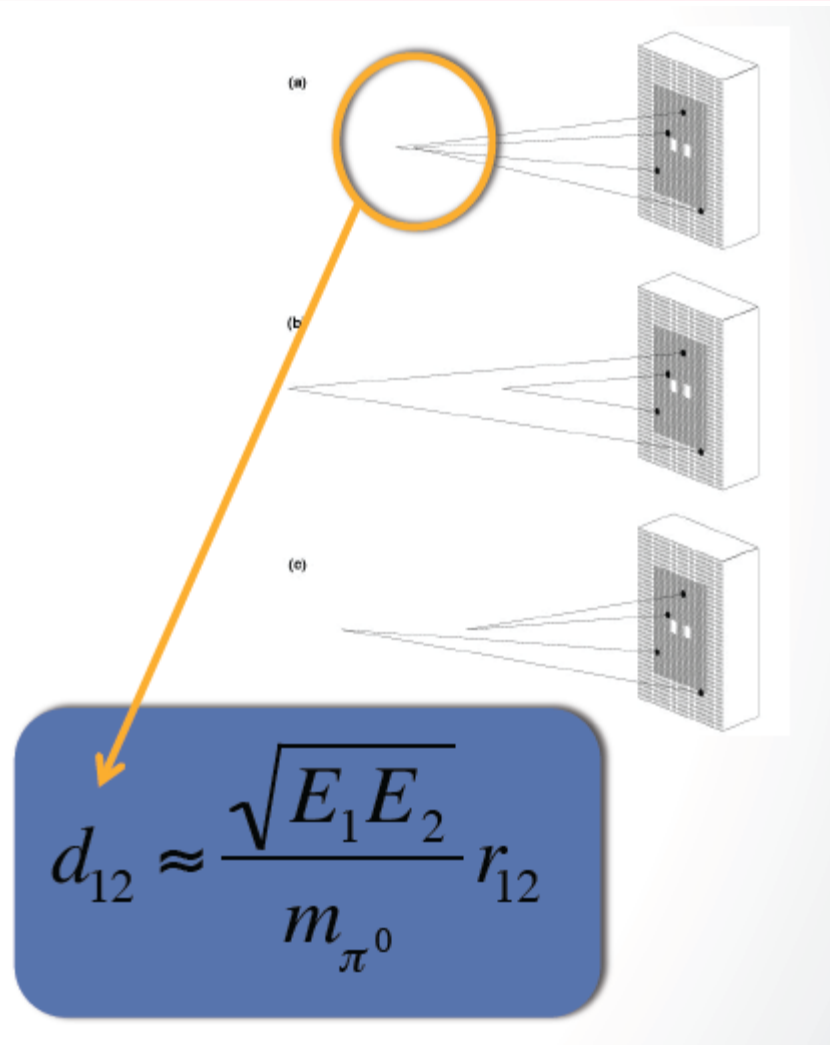
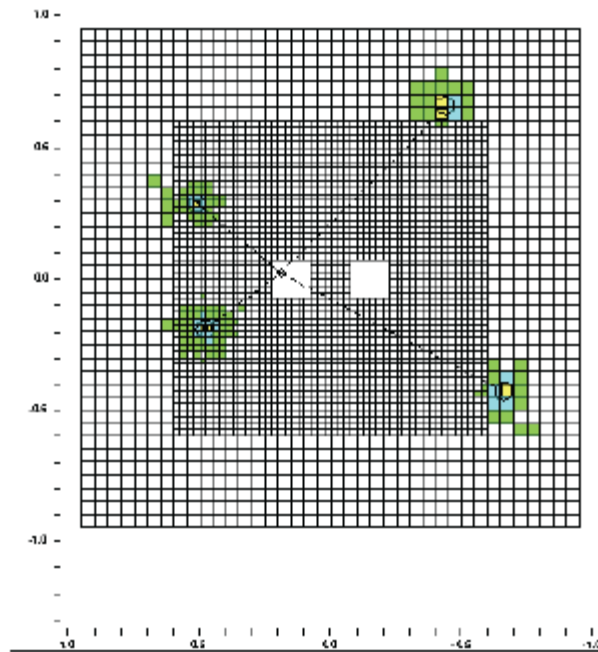




KTeV CsI calorimeter – $\pi^0\pi^0$ reconstruction

Signal is 4 photon showers in calorimeter

- Measure position and energy
- Use pion mass constraint to reconstruct decay vertex

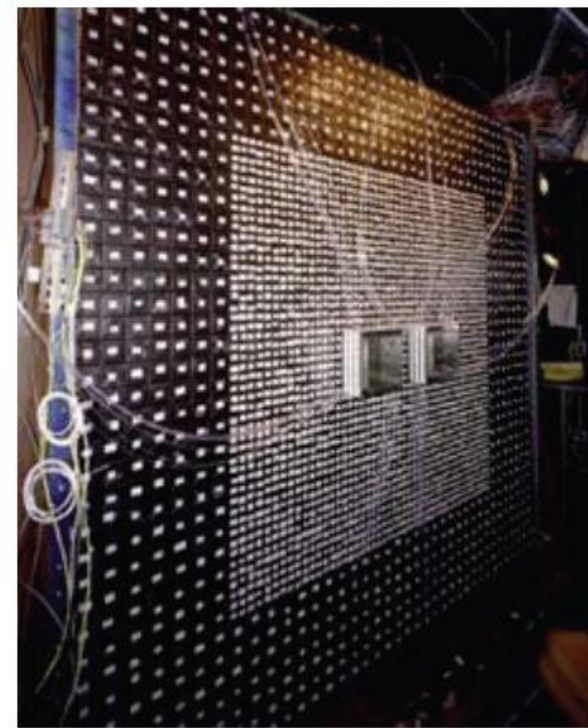


Elizabeth Worchester

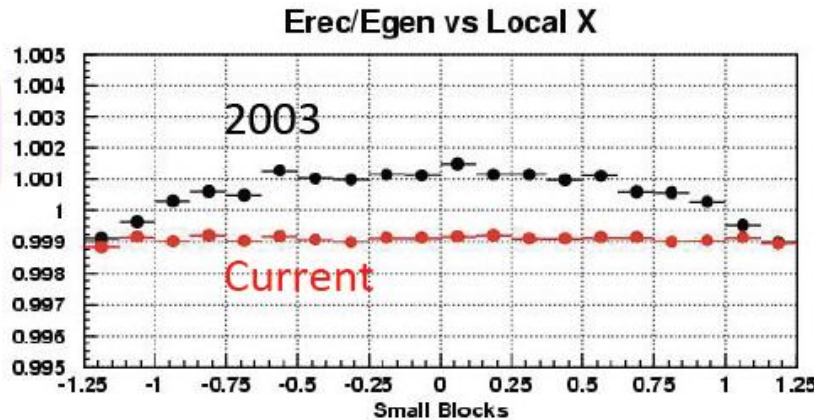


Small details matter

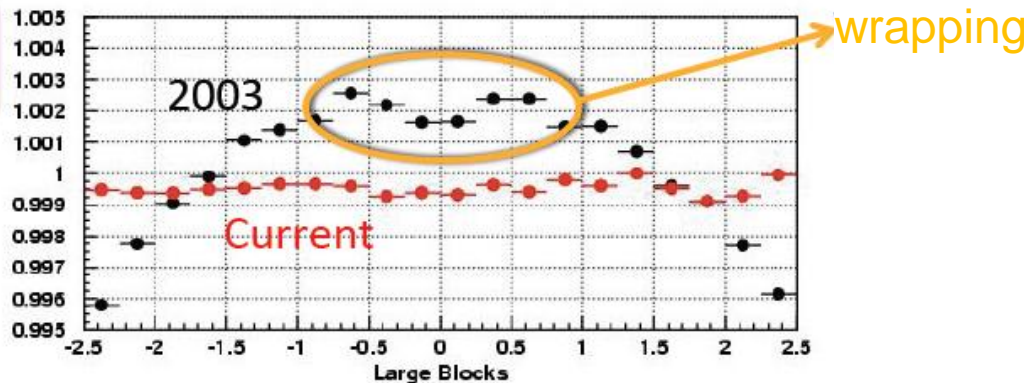
Simulation: Wrapping



Small
crystals



Large
crystals



- 3100 pure CsI crystals viewed by PMTs
 - Small crystals $2.5 \times 2.5 \times 50 \text{ cm}^3$
 - Large crystals $5.0 \times 5.0 \times 50 \text{ cm}^3$
- Calibrated by in-situ laser system and momentum analyzed electrons from Ke3 decays
 - Position resolution
 - $\sim 1.2 \text{ mm}$ (small crystals)
 - $\sim 2.4 \text{ mm}$ (large crystals)
 - Energy resolution $\sim 0.6\%$
 - Absolute energy scale $\sim 0.04\%$



KTeV calorimeter - conclusions

- KTeV Csl calorimeter extremely successful
 - E/p resolution $\sim 0.6\%$
 - Position resolution 1.2/2.4 mm
 - Longitudinal response uniform to $\sim 5\%$
 - Transverse response uniform to $\sim 1\%$
 - Energy non-linearity $< 1\%$
 - Reconstructed kaon mass linear within < 200 keV
 - Absolute energy scale known to $\sim 0.04\%$
- Design considerations
 - Reduce complications when possible
 - Redundant readout/easy access for replacement critical
 - Dead material important
 - Ability to reconstruct angles would have been great (timing? 3d?)
 - Extensive offline analysis required

Before final
corrections

After final
corrections

